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Impact of Phosphorus on Soil Organic Matter Dynamics in the Long-term, Classical Plots at Breton, Alberta

by

Shampa Chakraborty

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Impact of Phosphorus on Soil Organic Matter Dynamics in the Long-term, Classical Plots at Breton, Alberta submitted by Shampa Chakraborty in partial fulfillment of the requirement for the degree of Master of Science in Soil Science.

Dedication

To Mom, Dad and Mou
who pushed me to become a better, stronger person

Abstract

This study was conducted to assess the impact of phosphorus on soil organic matter dynamics in the long-term, 2-yr and 5-yr crop rotations at Breton, Alberta. Total soil P, extractable P, and crop yields in treatments with P were significantly higher than in those without P in both rotations. The amount of total soil C and N was higher in the 5-yr compared to the 2-yr rotation, and showed the following treatment trend: Manure > NPKS > NKS(-P) > Check. Mineralizable nutrients, and microbial biomass from the laboratory incubation experiments were significantly higher in the 5-yr compared to the 2-yr rotation. Liming increased soil pH but there was no significant difference in total C and N in the 5-yr rotation. The ratio of daily ^{15}N mineralization rate/total ^{15}N was significantly lower in treatments without P which showed that extractable P controls N mineralization under laboratory conditions.

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INTRODUCTION

The Breton Classical Plots were established in 1930 near the village of Breton by the Department of Soils, University of Alberta under the leadership of Dr. F. A. Wyatt and Dr. J. D. Newton and occupy 2.4 ha. Mr. Ben Flesher provided the land for the first plots in 1929, and did many of the plot operations including tillage, seeding and harvesting for a period of 40 years. The 8.46 ha parcel of land, on which the Breton Plots are located, was purchased by the University of Alberta in 1946. An additional 1.36 ha piece of undisturbed, virgin land adjacent to northwest corner of the Breton Plots was acquired in 1999. The Breton Plots were officially recognized as an Alberta Registered Historic Resource by the Provincial Department of Culture in July 1999 on the occasion of the 70th anniversary, and are known worldwide in the Soil Science Community. These plots are the only continuous, long-term plots on Gray Luvisols in Canada and possibly in the world (Fig. 1.1).

Fig. 1.1. Aerial view of the Breton Plots located 110 km SW of Edmonton, Alberta, Canada (53 ° 05', 9.5" N, 114° 25' 49.4" W)

AGROECOSYSTEM INFORMATION FOR THE BRETON CLASSICAL PLOTS

The Breton plots are located 110 km SW of Edmonton, Alberta, Canada (53 ° 05' 9.5" N, 114° 25' 49.4" W). The topography of the site is level to gently sloping (slopes 0 to 4%) with a southwest aspect. The soils of the area have developed on glacial tills derived mainly from sandstones and shales of freshwater origin (Paskapoo formation). Soil

formation was influenced by native vegetation consisting primarily of stands of white poplar (*Populus tremuloides*) and poplar-spruce (*Picea glauca*) combination. The land was settled and cleared circa 1920, and farmed prior to the preliminary trials of the formal experiment (1929). The Breton loam soil (Bn L, Orthic Gray Luvisol) has loam to silt loam texture in the surface horizon and is fairly well drained to well drained.

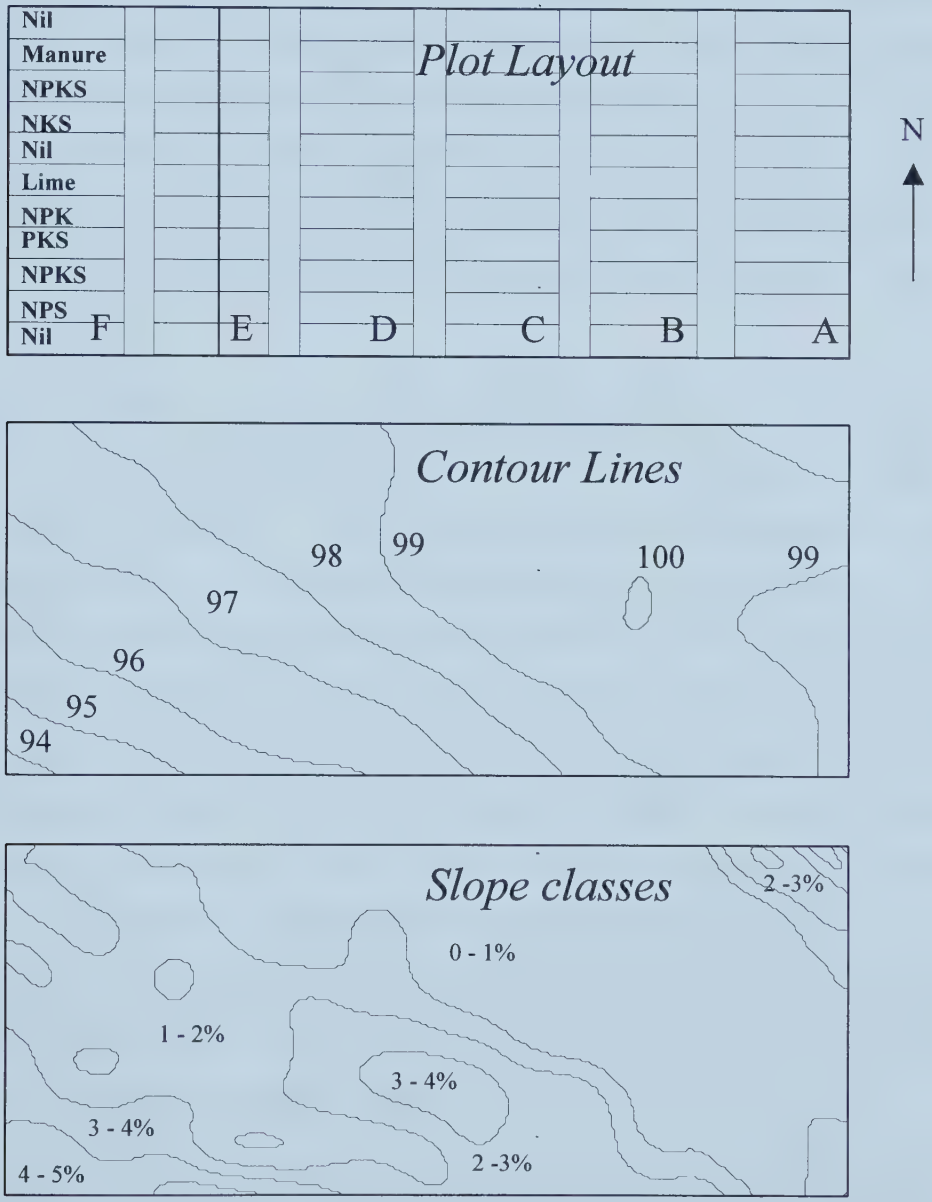

Fig. 1.2. Plot layout, contour lines spaced at 1-m vertical interval, and slope classes of the Breton Classical Plots (Izaurralde et al. 2001). The nil plots are referred as Check in the present study.

Preliminary fertilizer trials were conducted in 1929; the experiment was formally established in 1930. The experiment was designed to compare two cropping systems and test several soil amendments (fertilizers, manure, lime) within the two rotations. Originally, the experiment consisted of 5 blocks of land (Series A-E) which accommodated the 2 cropping systems, across which ran 11 strips with the various soil amendments. In 1937, an additional block of land was added (Series F) to expand the 4-yr rotation to a 5-yr rotation. Further, in 1941 the continuous wheat system (Series E) was split in half to create the present-day 2-yr rotation of Wheat-Fallow (Fig. 1.2). The forage species have varied over time: legumes alone were used (sweet/red clover or alfalfa/red clover) between 1930 and 1955; alfalfa, red clover, creeping red fescue, bromegrass and timothy between 1956 and 1966; and alfalfa and bromegrass from 1967 to the present.

The amounts of fertilizer, manure and lime applied to the Breton Classical Plots for the period 1930 to 1979 are presented in Table 1.1. The treatments and nutrient application rates were revised in 1980 to reflect currently recommended nutrient application rates and also to provide more valid comparisons among treatments. The two rotations were maintained but the nutrient application rates were changed to conform to practices for maximum yield. The design was also modified by implementing 'minus N', 'minus P', 'minus K' and 'minus S' treatments (Table 1.2) (Robertson and McGill, 1983). The original fertilizer rates were updated in 1980 Commercial fertilizer application methods have varied over the years; initially, fertilizers were annually broadcast, but from 1946-1963 fertilizers were broadcast every second year. In 1964, annual applications resumed and phosphates were drilled with the seed. In 1972, the east half of the 5-yr rotation plots (Series A-D and F) and complete plots of the 2-yr rotation (Series E) were limed up to 6.5 when pH dropped to ≤ 6.0.

The amendment treatments are not randomized and most were not replicated (Fig 1.2). The size of the whole plots (both the east and west halves) in both rotations is 31.5 m x 8.5 m. The crop(s) grown in each plot of the six series and the respective annual grain/straw or forage yields from 1930 to 1998 are accessible on-line at the Breton Plots website (http://bretonplots.rr.ualberta.ca/data/plot_form.html).

Table 1.1. Approximate fertilizer, manure and lime application rates to the Breton Classical Plots for the period 1930 -1979[a] (Cannon et al. 1984).

Plot	Treatments 1930-1979	Nutrients added (kg ha^{-1} yr^{-1})			
		N	P	K	S
1	Check	0	0	0	0
2	Manure (M)[b]	76	42	91	20
3	NPKS	10	6	16	10
4	NS	11	0	0	11
5	Check	0	0	0	0
6	Lime (L)	0	0	0	0
7	LNPKS[c]	0 (11)	10 (6)	0 (16)	1 (9)
8	P	0	9	0	1
9	MNPS	86	48	91	28
10	NPS	10	6	0	8
11	Check	0	0	0	0

[a] In 1944-1963, fertilizer was applied every second year at rates approximating N (9), P (5), K (14) and S (8) kg ha^{-1} each year.

[b] Applied every fifth year, in later years at 44 t ha^{-1}. Nutrient rates are annual equivalents and are estimates based on manure applied from 1976-1986 inclusive.

[c] This treatment was initially a lime (L) plus phosphorus (LP) treatment. In 1964, it became LNPKS. In 1980, it became NPK treatment. Nutrient application rates thereafter are shown in brackets.

[d] Lime was broadcast and tilled onto plot 6 and 7 several times between 1930 and 1948 for a total application of approximately 6.6 t ha^{-1}. No lime was applied to plots 6 and 7 between 1949 and 1979, but all the other plots in Series E and the east half of all other plots in series A, B, C, D and F were limed to pH 6.5 in 1972.

Table 1.2. Revised treatments, and fertilizer and manure application rates to the Breton Classical Plots from 1980 onwards (Cannon et al. 1984).

Plot	Treatments 1930-1979	Nutrients added (kg ha^{-1} yr^{-1})			
		N	P	K	S
1	Check	0	0	0	0
2	Manure	a	-	-	-
3	NPKS	b	22	46	5.5
4	NKS(-P)	b	0	46	5.5
5	Check	0	0	0	0
6	Lime	0	0	0	0
7	NPK(-S)	b	22	46	0
8	PKS (-N)	0	22	46	5.5
9	NPKS[c]	b	22	46	5.5
10	NPS(-K)	b	22	0	5.5
11	Check	0	0	0	0

[a] N application via manure depends upon the rotation. The 2-yr wheat-fallow rotation receives equivalent of 90 kg N ha^{-1} for each wheat crop. The 5-yr cereal-forage rotation (wheat, oat, barley, forage and forage) receives 176 N ha^{-1} every 5 years. Since 1980, manure is added at the rate of 88 kg N ha^{-1} per application after oat harvest and at the time of second forage plow down.

[b] N amounts depend on the crop and its place in rotation: Wheat after fallow 90 kg ha^{-1}; wheat after forage 50 kg ha^{-1}; oat after wheat 75 kg ha^{-1}; barley after oat 50 kg ha^{-1}; legume-grass forage after barley 0 kg ha^{-1}: forage after forage 0 kg ha^{-1}.

[c] The B horizon in the NPKS treatment of plot 9 ripped to a depth of 75 cm in 1983.

The grain crops are harvested in the fall, usually between August 20 and September 15, depending on the weather. The first year forage crop is cut twice seasonally: the first cut is in early July and the second is in September. The second year forage crop is harvested in July and the plot is clean cultivated for the end of the season. For all treatment combinations, almost all above ground growth have been removed (straw, grain and hay) and no crop residues are returned to the soil. The plots are tilled once in the fall after harvest and again in the spring prior to planting. Planting is currently done with a press drill; planting usually occurs between May 1-15. The current seeding rates are 82 kg ha^{-1} for wheat; 89 kg ha^{-1} for oats and barley; 10 kg ha^{-1} and 15 kg ha^{-1} for alfalfa and bromegrass, respectively. All seeds are planted in 15 cm rows.

Fertilization rates are dependent on the particular crop and its place within the rotation and are described in Table 1.2. Herbicides were used in 1960 onward, first to control broad leaf weeds and later to control wild oats. Standard recommended practices were used to select the types and rates of herbicide for particular cropping sequences. Weeds in the fallow plots in the 2-yr rotation are controlled with tillage and/or herbicides. Lime was added to the east half of the 5-yr rotation plots (Series A-D, and F) and to the complete plots of the 2-yr rotation (Series E) in 1972. Soil pH is measured every five years and lime is added whenever it is <6.5 (Juma et al. 1997a).

OVERVIEW OF MAJOR DISCOVERIES AT THE BRETON PLOTS

Dr. Wyatt, Dr. Newton and Mr. Flesher are recognized as the founders of the Breton Plots. They designed the plots to find "a system of farming suitable for the wooded soil belt" (Robertson 1979). However, these plots have provided information on: (1) aspects of nutrient deficiencies, soil acidity and acidification by fertilizers, liming, soil tilth, and quality of feeds grown (Bentley et al. 1960; Robertson, 1979) and (2) carbon sequestration (Juma et al. 1997b; Janzen et al. 1998; Izaurralde et al. 2001; Grant et al. 2001) and (3) greenhouse gas evolution (Carcamo 1997; Lemke et al. 1998). The results of accumulated research are currently being used to predict carbon sequestration and greenhouse gas production under changing climate scenarios, and are being extrapolated to toposequence, landscape and global scales. The plots are also being used to address

issues of soil, air and water quality. A searchable list of publications is available on line at the Breton Plots website (http://bretonplots.rr.ualberta.ca/publications.html).

An overview of major discoveries over the past 70 years is presented below. This will be followed by pertinent information for articulating the research problem and hypotheses.

Overcoming Nutrient Deficiencies (The 1930's to 1960's)

1. Gray Luvisolic soils are quite deficient in sulfur (S) (Newton 1936). This was a significant and original discovery because there were few previous reports of S deficiency of such soils in the world at that time. Increases in crop yields in these soils could be obtained from the addition of nitrogen and sulfur in such fertilizers as manure, ammonium sulfate (21-0-0) and ammonium-phosphate-sulfate (16-20-0), especially in rotations incorporating legumes (Wyatt 1936). Besides these discoveries, it has been shown that added phosphorus also is beneficial as long as adequate nitrogen and sulfur is added (Odynsky 1936, Newton 1954, Bentley et al. 1960).
2. Summer fallowing is unnecessary in Gray Luvisols because these soils usually receive adequate rainfall. The practice of summer-fallowing is especially destructive in Gray Luvisols because these soils have low organic matter content (Toogood and Lynch 1959).

Improving Soil Quality (1930's to 1990's)

1. Soil tilth, as observed visually and measured by water-stable aggregates, has been much improved on the plots in the 5-yr cereal-forage rotation (wheat, oat, barley, forage, forage). The improved tilth is associated with higher levels of polysaccharides (Toogood and Lynch 1959), presumably due to increased microbial activity. The benefit probably arises because of the fibrous grass roots in the forages, the higher fertility status of the soil, and the reduced time that the soil is crop-free. The Breton Classical Plots are one of the few places in Canada where it has been possible to demonstrate an effect of consistent management on soil tilth.

2. The Breton Plots have shown that long-term application of even low rates of ammonium fertilizers will lower soil pH (McCoy and Webster, 1977) so that crop production is reduced, either because of unfavorable effects on Rhizobium and/or development of toxic levels of aluminum and manganese. Modified treatments begun in 1972 show the beneficial effects of adding lime.

3. Manure at 9 tonnes/ha/year has been very beneficial. It was one of the highest yielding treatments till 1980, partly because it supplied much more nitrogen than do any of the commercial fertilizer treatments (Table 1.1) and it has not changed the soil pH compared to check plots.

4. Using longer crop rotations (5-yr and longer) that include forages increases crop yield and soil organic matter, with simultaneous improvement of soil structure as measured by the mean weighted diameter of soil aggregates (Toogood and Lynch 1959).

5. The soil organic C (SOC) in the Manure treatment of the 5-yr rotation after 51 years of cultivation (1939-1990) was 25 Mg ha^{-1} more than the Check in the 2-yr rotation (Izaurralde et al. 2001). Grant et al. (2001) simulated the changes of soil C over a period of 70 years (1930-2000) and found that soil C declined at the rate of 14 and 7 g C m^{-2} y^{-1} in the 0.15 m depth of the Check and NPKS treatments of the 2-yr rotation; by gains of 7 g C m^{-2} y^{-1} in the Manure treatment of the 2-yr rotation; and by gains of 4, 14, and 28 g C m^{-2} y^{-1} in the Check, NPKS and Manure treatments of the 5-yr rotation. Similar trends have been reported for microbial biomass C and N, soluble C, and available N, P, and S (Campbell et al. 1997).

Assessment of Air and Water Quality (The 1990's):

1. Nitrate accumulation in wheat-fallow and wheat-oat-barley-hay-hay rotations ranged from 0 - 67 kg N/ ha at depths from 0.9 to 3.9 m. There was a tendency for the 5-yr rotation to store more NO_3- N in the rooting zone (0 to 0.9 m) and less below the rooting zone, compared to the 2-yr rotation (Izaurralde et al. 1995).

2. Greenhouse gas emissions were quantified on Breton Classical Plots (Carcamo 1997). Potentially mineralizable carbon measured for 14 weeks was 30% higher in the 5-yr rotation compared to the 2-yr rotation.

Assessing Local and Global Impacts (2000 and beyond):

Important future research topics include the following: carbon, nitrogen, sulfur and phosphorus cycling; landscape dynamics of water, carbon and nutrients; soil aggregate dynamics; greenhouse gas emissions; nitrate leaching; biodiversity under diverse crop and soil management; impact of changing CO_2 on crop and soil productivity; legumes and forages in rotations; weed control; use of manure as a resource; input of S from industrial emissions; and agroecosystem modeling.

Fig. 1.3. A conceptual diagram showing the potential of the Breton Plots to unravel the interconnectedness of air, soil, and water quality and biodiversity

The Breton Classical Plots are a living library of invaluable information on the impact of consistent, long-term management on soil quality and crop productivity and have a great potential for being used to assess the impact of management on soil, air and water quality and biodiversity in the future (Fig. 1.3).

GENERAL BACKGROUND FOR THIS STUDY

Composition of Soil Organic Matter

Soil organic matter consists of living or dead plant material, living organisms, products derived from microbial and faunal metabolism, and stabilized, complex organic material called humus. Chemically, soil organic matter primarily consists of C, H, O, N, S, and P. The surface horizons of mineral soils contain >90% of soil C, N, and S in organic forms but only 40% of soil P is present in organic forms (Smith et al. 1993). The remainder of soil P is present in mineral forms.

Almost all of organic N is directly bonded to soil organic C in surface horizons. In contrast, almost all of the organic P is bound to carbon via ester linkages (C-O-P). Organic S is directly bonded to C and also present as esters in soil organic matter. Under net mineralization conditions, there are stoichiometric relationships between C, N and S mineralized. However, such relations are not possible between C mineralized and soluble inorganic P because the latter is in equilibrium with adsorbed and occluded forms of inorganic P. The inorganic P is readily immobilized and remineralized by plants and microorganisms, therefore the P cycling is more complex than C, N or S cycling (McGill and Cole 1981).

Dynamics of Soil Organic Matter

The amount and quality of soil organic matter (SOM) at a point in time reflects the culmination of complex interactions between physical, chemical and biological processes which occur within and above the soil (Jenkinson 1988). Soil organic carbon (SOC) in agro-ecosystems may increase, decrease or remain unchanged as a result of the balance between gains (net primary productivity, amendments) and losses (soil respiration, erosion) (Izaurralde et al. 2000). The soil can be a source or a sink for atmospheric CO_2 depending upon agroecosystem management (Paustian et al. 1997; Janzen et al. 1998), land use and vegetative cover change (Greenland 1995).

Studies of soil organic matter and cycling of N, P and S emphasize the central role of organic C as a driving force for nutrient cycling. The changes in plant available nutrients are controlled by physical, chemical and biological interactions in soil. Mineralization

denotes the overall process by which organic forms of N, P, S are transformed by soil biota into ammonium, inorganic phosphate, and sulfate. The opposing and intrinsically-linked process of immobilization denotes the conversion of inorganic forms of N, P, and S due to synthetic reactions associated with growth and metabolism of soil biota, especially soil microbes. The processes of mineralization and immobilization of N, P, and S together constitute the internal heterotrophic sub-cycles in soil.

The key to understanding the dynamics of crop nutrient availability and soil carbon sequestration is intimately tied to the dynamics of soil organisms. Crops play a vital role of supplying organic carbon substrates which provide energy and building blocks for soil biota. The biota, in turn cycle the nutrients and build soil structure, and contribute to crop growth and development through these activities. Decomposition and turnover of SOM supply most of the nutrients needed for plant growth.

Importance and Availability of Phosphorus

Phosphorus is an essential nutrient for plant growth and development. Crops become stunted and spindly and develop poor or no seed under P limiting conditions. Phosphorus is needed for DNA synthesis and energy transfer/production in soil microbes and plant cells. Most microbial processes like mineralization, N fixation and immobilization require P to carry these essential functions.

Dissolved inorganic P (Pi) from inorganic fertilizers, manure or indigenous soil sources reacts with soil constituents to create less soluble forms (Fig. 1.4). A number of mechanisms have been proposed to explain P retention in soil: precipitation-dissolution reactions, sorption-desorption reactions and mineralization immobilization reactions. Soluble Pi is rapidly adsorbed or desorbed by charged soil constituents. These processes may be of a greater significance than precipitations-dissolution reactions (Tisdale et al. 1993). A variety of virtually insoluble inorganic P compounds are formed with Fe^{3+} and Al^{3+} at low pH. As the soil pH increases towards neutrality, Ca^{2+} and Mg^{2+} compounds are more soluble and increase the availability of P. In the alkaline pH ranges, Pi is found on virtually insoluble Ca compounds. Phosphates also react with clays to form generally insoluble clay-phosphate complexes (Tisdale et al. 1993).

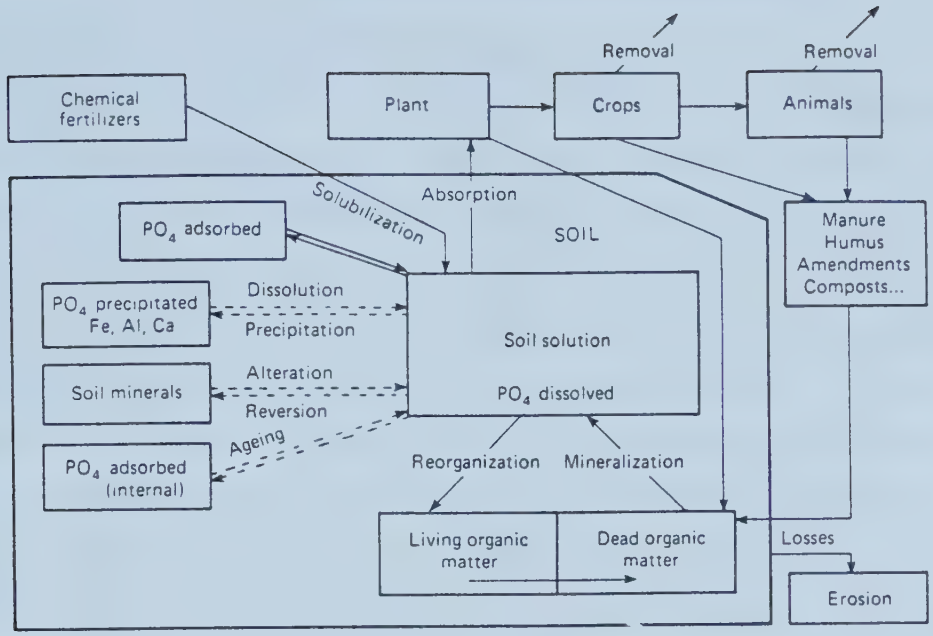

Fig. 1.4. Phosphorus dynamics in a soil (Tisdale et al. 1993)

The organic forms consist of inositol phosphates, nucleic acids phospholipids and esters. Organic forms of P (Po) range from soluble organic P to stable forms of P in humus. Therefore, various kinds of extraction schemes have been developed to measure different components of the P cycle in soil (Fig. 1.5)

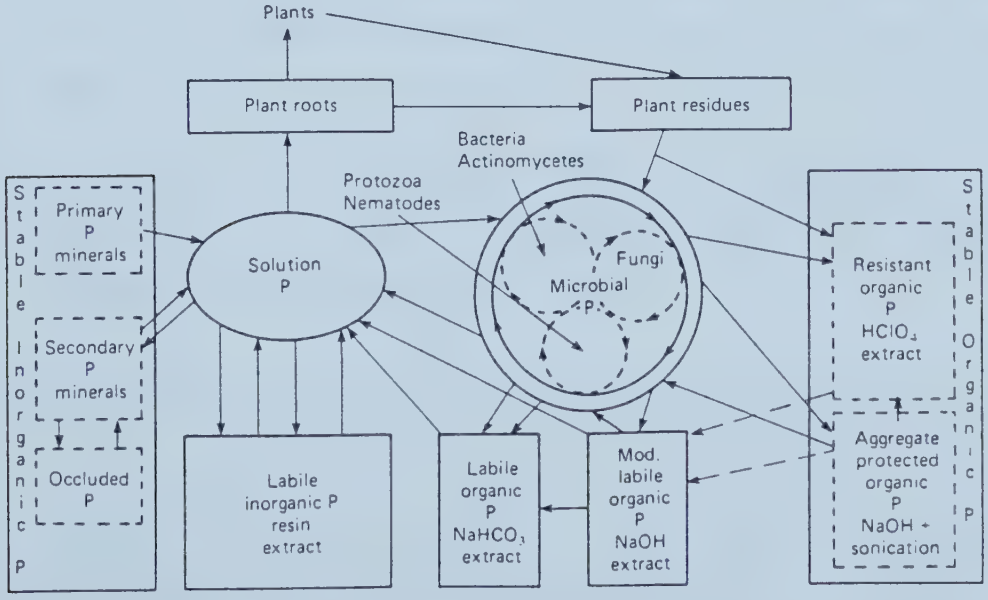

Fig. 1.5. Schematic illustration of the measurable components of the P cycle in soils, showing the interchange of solution, organic and microbial forms (Chauhan et al. 1981).

OBJECTIVES FOR THIS STUDY

The physical, chemical and biological properties of soils in the Check, Manure and NPKS treatments in 5-yr and 2-yr crop rotations of the Breton Classical Plots have been extensively studied and results from a large number of studies have been synthesized by Campbell et al. (1997). The data from these three treatments of the two, long-term crop rotations have also been analyzed using regression and simulation models (Grant et al. (2001); Izaurralde et al. (2001)). Recent focus has been on the impact of rotations and treatments on soil carbon sequestration and nitrogen dynamics. However, both the impact of P on C and N dynamics over the long term has not been examined. In this study, an additional treatment, NKS(-P), was used to assess the impact of P added as inorganic fertilizer and manure on soil organic matter dynamics. This four treatments (Manure, NPKS, NKS(-P) and Check) of the 5-yr and 2-yr long-term crop rotations of the Breton Classical Plots were used for this project.

The objectives of this project were to assess the impact of:

1. phosphorus on crop yields, and dynamics of soil organic matter in four limed treatments of 5-yr and 2-yr crop rotations at Breton, Alberta (Chapter 2);

2. liming and phosphorus on crop yields and dynamics of soil organic matter in four limed and unlimed treatments of the 5-yr rotation at Breton (Chapter 3); and

3. phosphorus on soil organic matter dynamics in ^{15}N-labeled soils in four, limed treatments of the 5-yr and 2-yr crop rotations at Breton, Alberta under laboratory conditions (Chapter 4).

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Chapter 2. Impact of Phosphorus on Soil Organic Matter Dynamics in the 2-yr and 5-yr Long-term, Crop Rotations at Breton, Alberta

INTRODUCTION

Gray Luvisols have several properties, which are problematic for agricultural management (Cannon et al. 1984). The mineral surface horizon (A) is thin, and is low in organic matter (about 2-3 %) and nutrient supplying power. The A horizon is also slightly acidic (pH 6.0-6.5) and has poor tilth when cultivated. These soils also have an illuvial Bt horizon that is firm and acidic (McGill and Robertson 1983).

The Breton Classical Plots, located near Breton, Alberta, Canada were established in 1930 to find a suitable method of farming on Gray Luvisols. Two crop rotations have been studied over the past 70 years: (1) a 2-yr wheat and fallow rotation; and (2) a 5-yr cereal-forage rotation consisting of wheat, oat, barley, forage and forage. The physical, chemical and biological properties of soils in the Check, Manure and NPKS treatments in both rotations have been extensively studied and results from a large number of studies have been synthesized by Campbell et al. (1997).

The major discoveries at the Breton Classical Plots with respect to C and N dynamics in the two crop rotations are: (1) The soil organic C (SOC) in the 0-15 cm depth of the Manure treatment of the 5-yr rotation after 51 years of cultivation (1939-1990) was 25 Mg ha^{-1} more than the Check in the 2-yr rotation (Izaurralde et al. 2001); (2) Soil organic C declined over a period of 70 years (1930-2000) at the rate of 14 and 7 g C m^{-2} y^{-1} in the 0.15 m depth of the Check and NPKS treatments of the 2-yr rotation; increased by 7 g C m^{-2} y^{-1} in the Manure treatment of the 2-yr rotation; and increased by 4, 14, and 28 g C m^{-2} y^{-1} in the Check, NPKS and Manure treatments of the 5-yr rotation (Grant et al. 2001); (3) Microbial biomass C was significantly higher in the manured plots (571 mg kg^{-1}) than the Check (389 mg kg^{-1}). The average turnover rate of microbial biomass for the 2-yr rotation was 1.08 yr^{-1} for the manure treatment, 1.02 yr^{-1} for the NPKS and 1.29 yr^{-1} for the Check; in the 5-yr rotation the turnover rate was 0.55 yr^{-1} for the Manure treatment, 0.93 yr^{-1} for the NPKS, and 1.33 yr^{-1} for the Check (McGill et al. 1986); and (4) The trends of microbial biomass C and N, soluble C, and available N were correlated to changes in soil organic matter (Campbell et al. 1997).

Janzen et al. (1992) suggested that changes in soil and crop management may be more readily observed in differences in short term indicators such as the light fraction and macro-organic matter (MOM) fraction than changes in total soil organic matter. Thus, the short term indicators would show the direction of change of soil organic matter in response to consistent management practices. Campbell et al. (1997) showed that the short-term indicators are correlated to total soil C, N, and P. Therefore, at the Breton, Classical Plots it is desirable to corroborate their results.

Available soil P in different treatments of the Breton Classical Plots was first assessed in 1957. The amount of Olsen-P in the 5-yr rotation was greatest in the Manure treatment (Manure > NPKS = Check) (Toogood et al. 1962). McKenzie et al. (1992) used the Hedley fractionation technique to assess changes in forms of soil P in the Check and NPKS treatments of both rotations. The biologically available Pi fraction showed greater draw down in the Check plot of the 5-yr rotation than in the less frequently cropped 2-yr rotation. However, both the dynamics of soil P and its impact on C and N dynamics over the long term and the differentiation between the P in the Manure and NPKS treatment have not been extensively studied. The NKS(-P) treatment in the Breton Classical Plots may provide new insights to the effect of P on soil organic C and N dynamics.

The objective of this study was to assess the impact of phosphorus on crop yields, and dynamics of soil organic matter in four limed treatments (Manure, NPKS, NKS(-P) and Check) of 5-yr and 2-yr crop rotations at Breton, Alberta.

MATERIALS AND METHODS

The Breton Classical Plots

The University of Alberta Breton plots are located at 53° 05' N, 114° 26' W. The dominant soils at the plots are Orthic Gray Luvisols and Dark Gray Luvisols. The Breton Classical Plots were set up in 1930 were to compare two cropping systems and examine several soil amendments within the two rotations (Robertson 1979). The original cropping systems were continuous wheat (*Triticum aestivum* L.) and a 4-yr crop rotation with three cereal grain years and one legume year. In 1941, the continuous wheat plot

was split in half to become a wheat-fallow rotation. In 1937, the 4-yr rotation was converted to a 5-yr rotation consisting wheat, oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), forage, forage. The forage crop varied over the years but always included a legume (Juma, 1995). Between 1939-1954, the forage component consisted of "mixed legumes" and between 1955-1966, a five crop mix of alfalfa (*Medicago sativa* L), red clover, (*Trifolium pratense* L.), bromegrass (*Bromus inermus* Leyss), creeping red fescue (*Festuca rubra* L), and timothy *(Phleum pratense* L). Since 1967 the forage mixture has been changed to alfalfa and bromegrass because these were most commonly recommended as a forage mixture in the area.

All phases of the two rotations with specific fertilizer and/ other amendment are present each year, however the plots are not replicated. The fertilizers included several combinations of macro nutrients (including nitrogen, phosphorus, potassium, and sulfur), amendments included lime ($CaCO_3$), and farmyard manure. Fertilizer application methods varied over the years. Initially, all fertilizers were annually broadcast, however, from 1946-1964, fertilizers were broadcast every second year. In 1964, additions of fertilizer resumed to annual applications in which the phosphate was drilled with the seed.

The average fertilizer application rates from 1930 to 1979 for N, P, K, and S were 10, 6, 16, and 10 kg $ha^{-1}year^{-1}$, respectively. After 1980 the fertilizer applications for P, K and S were 22, 46, and 5.5 kg ha^{-1} $year^{-1}$, respectively. The amount of N applied after 1979 was a function of the crop type and its place in the rotation: 2-yr rotation: wheat after fallow - 90 kg N ha^{-1}; 5-yr rotation: wheat after second forage - 50 kg N ha^{-1}; oat after wheat - 75 kg N ha^{-1}; and barley after oats - 50 kg N ha^{-1}. No N fertilizer was applied to forage crops. Manure was originally applied up to 1979, once every five years at the rate of 44.8 Mg ha^{-1} in both rotations and was added after the second forage crop was harvested in the 5-yr rotation. However, from 1979 to present, the manure N application is a function of the particular crop rotation: 2-yr rotation - 90 kg N ha^{-1} for each wheat crop; 5-yr rotation-175 kg N ha^{-1}, applied in two equal applications at the rate of 88 kg N ha^{-1} per application after oat harvest and at the time of forage plow down. In 1972, lime was added to the east half of all plots in the 5-yr rotation and to the entire area

of the 2-yr rotation. Control plots have not received any fertilizer or amendment since 1930, with the exception of lime on the east halves in 1972 when the pH ≤ 6.0.

The original order of the treatments from north to south was (1) Check; (2) Manure (M); (3) NPKS; (4) NS; (5) Check; (6) Lime (L); (7) LP (NPKSL in 1964); (8) P; (9) MNPS; (10) NPS; and (11) Check. From 1980, the treatment order has been changed to (1) Check; (2) M; (3) NPKS; (4) NKS; (5) Check; (6) L; (7) NPK; (8) PKS; (9) NPKS (subsoil); (10) NPS; and (11) Check (Cannon et al. 1984). The crops in the 5-yr rotation are rotated over series A, B, C, D, and F. The crops are alternated between the two halves of the plots in Series E.

Sampling

Soil samples were collected from the east sides of plot treatments 1, 2, 3, and 4 in Series A, B, C, D, and F of the 5-yr rotation and Series E (east-fallow and west-wheat) of the 2-yr rotation in October 1998. The samples in these series were taken from the following plot treatments: Check, Manure, NPKS and the NKS(-P). Each half-plot was sampled using a coring truck and a steel coring tube (length of 50.8 cm and 7.6 cm diameter). Three cores were taken from each half-plot. The 2-yr rotation (Series E – wheat/ fallow) split plot was limed on both sides, from which both were sampled. The depths of sampling included the following: 0-7.5 cm, 7.5-15 cm, 15-30 cm, and 30-45 cm. The soil cores from each half-plot were composited, air dried and measured for moisture content and bulk density according to the protocol described by Ellert and Johnson (1997). Bulk density was calculated based on dry soil and adjusted volume of soil in the coring tube. Stones found in the samples were weighed and volumes calculated. These were subtracted from the soil to give the adjusted mass and volume of soil. Thus, the bulk density was calculated for the soil samples without stones.

Measurements

The soil total C and N were measured using a Carlo Erba NA1500 C and N Analyser (Ellert and Johnson 1997). For total soil P, soil samples were digested by the Kjeldahl method at 360 °C for 4.5 h with H_2SO_4, K_2SO_4, and Selenium and the digests were

analyzed for total P on Technicon 4000^{tm} Autoanalyser (Technicon 1977a). Soil pH was measured using 10 g soil to 20 mL 0.01M $CaCl_2$. The sample in solution was stirred for 10 minutes and allowed to settle for 3 hours. The supernatant was measured by the Fisher Accumet pH Meter Model 630 (bottom of electrodes were approximately 2 cm above from the settled soil).

Soil macro-organic matter (MOM) was separated and weighed from air dried soil using the sieving/winnowing procedure (Ellert and Johnson 1997). Separation was done only in the 0-7.5 cm and 7.5- 15 cm samples. Total C and N in the MOM were measured by the same method as for total C and N for soil samples. The total P in the MOM fraction was determined using Kjeldahl digestion with sulfuric acid (6M) and hydrogen peroxide to remove all organic forms of P at 360 °C for 1.5 h and analyzed on Technicon 4000^{tm} Autoanalyser (Technicon 1977a).

A bioassay of the soil samples, without the MOM fraction, from the 0-7.5 cm and 7.5-15 cm depths was conducted to quantify the C and N mineralization as outlined by Ellert and Johnson (1997). The air dried samples (approx. 75 g oven-dry equivalent basis) were incubated at 22 °C at 80% field capacity moisture for a total of 70 days. Moisture content was determined by weighing a known volume of wet soil, drying it at 105 °C for 24h and weighing the oven dry soil. Field capacity was determined by filling a weighed clear plastic tube (about 10 cm length and 5.5 cm diameter) with air-dried soil up to 7.5 cm length of tube, weighing the soil and tube, and adding water to the tube until the soil is wet to about 2.5 cm from the bottom. The tube with wet soil was weighed and left to stand for 48 hours. The moist soil was weighed, dried and reweighed to determine the amount to water needed to bring the soil to field capacity (Molina-Ayala, pers. comm. 1998).

The samples, in polyethylene specimen cups, were placed in 2L mason jars along with a small vial containing 10 mL of 2M NaOH to trap CO_2 evolved from the soil sample. The traps were changed after 7 days, 28 days and 70 days and titrated with standardized HCl solutions (1M and 0.1M).

Biological and chemical methods have been developed as indices of nutrient availability. Microbial C was analyzed after the 10 week incubation using the chloroform fumigation extraction technique as outlined in the methods of Ellert and Johnson (1997). The soluble C was measured and divided by a K_{CE} factor of 0.25 (Voroney et al. 1993). To measure soluble C the soil was extracted (25 g) with 0.125 M K_2SO_4 (80 mL) for 30 minutes and the filtrates analyzed in the Astro 2001 soluble carbon analyzer (Astro Texas U.S.A.). Mineralized nitrogen was extracted using KCl as the extractant. Approximately 20 g of oven-dry equivalent soil samples was shaken for 1 hour with 80 mL 2M KCl, then filtered on No 2 Whatman Filter paper. The extracts were analyzed for mineral N (NH_4^+ and NO_3^-) on a Technicon 4000^{tm} Autoanalyser (Technicon 1977b, 1978). The N mineralized during 10 weeks was the difference between post- and pre-incubated samples.

Available P was determined using the modified Kelowna method, originally formulated by Olsen and Sommers (1982). Air dried soil samples (10 g oven dry equivalent) were extracted with 50 mL of Kelowna extract (0.015 M NH_4F, 0.10 M CH_3COOH). After 30 minutes of mechanical shaking and filtering through Number 2 Whatman Filter paper the PO_4- P was analyzed on a Technicon 4000^{tm} Autoanalyser (Technicon 1973).

Statistical Analysis

The General Linear Models Procedure of SAS (Statistical Analysis System 1990) was used to analyse the experimental data due to the imbalance of replicates. A three factor ANOVA with the Duncan and Bonferroni (Dunn) Multiple range t tests were used to test for the rotation treatment, and depth effects. The results are averages of the number of replicates (ie. the number of crop years) in each rotation (2 for the 2-yr rotation and 5 for the 5-yr rotation). The wheat yields from each rotation were averaged from 1972-1998. The datum for each year was considered as a replicate. Rotation, treatment, and depth were the main factors in the analysis of variance for all soil, MOM and short-term indicator soil samples.

RESULTS

Spring wheat grain and straw yield trends from 1972- 1998 for all four treatments in the 2-yr and 5-yr rotations

The average grain and straw yields from 1972 to 1998 were greater in the 5-yr rotation than those in the 2-yr rotation. The average grain and straw yields in the 5-yr rotation were Manure > NPKS > NKS(-P) = Check while in the 2-yr rotation they were NPKS > Manure > NKS(-P) > Check (Table 2.1). Average grain yields ranged from 2920 kg ha^{-1} in the 5-yr Manure to 820 kg ha^{-1} in the 2-yr Check. Average straw yields ranged from 4530 kg ha^{-1} to 1320 kg ha^{-1}. The average grain and straw yields from the 5-yr rotation were 1.2 times higher than the yields of the 2-yr rotation. The yields in the Manure and NPKS treatments were about 1.7 times higher than those in the NKS(-P) and Check treatments.

Soil Bulk Density and pH, soil total C, N and P, and soil C:N:P ratios in the 0-7.5, 7.5-15, 15-30 and 30-45cm depths.

The average soil bulk density was significantly lower in 5-yr rotation compared to the 2-yr rotation in all depths (Table 2.2). The bulk density in the NKS(-P) treatment was similar to that in the NPKS and Check treatments but it was significantly higher compared to the Manure treatment. The bulk density significantly increased with depth, however there was a significant rotation by depth interaction. The bulk density significantly increased below the 7.5 cm depth the 2-yr rotation and below 15 cm in the 5-yr rotation (Table 2.2). In the 0-7.5 cm depth, bulk densities in the 5-yr rotation ranged from 1.2-1.3 g cm^{-3} compared to 1.2-1.4 g cm^{-3} in the 2-yr rotation. In the 7.5-15 cm depth, bulk densities ranged from 1.3-1.4 in the 5-yr rotation and 1.4-1.5 g cm^{-3} in the 2-yr rotation.

Soil pH values differed significantly between both rotation and treatment (Table 2.2). However, there were no significant differences in pH values among depths. The average pH in all depths in the NKS(-P) treatment plots of both rotations was approximately 0.2 units lower compared to the Manure treatment. The 2-yr rotation, in general, had a higher average pH by 0.2 units. The exceptions were the 15-30 and 30-45 cm depths of the 2-yr NKS(-P) treatment with pH values of 6.1 and 6.0, respectively.

The average total C in the 0-7.5 cm depth of the 5-yr rotation for (18,400 kg ha^{-1}) was higher than that in the 2-yr rotation (12,500 kg ha^{-1}); the average total soil C contents in the 0-7.5 cm were higher in the Manure (20,500 kg ha^{-1}) and NPKS (14,500 kg ha^{-1}) treatments compared to NKS(-P) (14,300 kg ha^{-1}) and Check (12,600 kg ha^{-1}) treatments; There were significant increases in total C observed in the 2-yr NKS(-P) and Check between the 7.5-15 cm and 15-30 cm depth but total soil C significantly only decreased with depth in the 5-yr rotation, in the depths of 15 cm or lower. Trends in the lower depths resembled those in the surface depth but the magnitude was lower. The trend of average total C (kg ha^{-1}) with respect to depths was: 15,500 (0-7.5 cm) > 13,400 (7.5-15 cm) > 12, 200 (15-30 cm) and 9,200 (30-45 cm).

The trends of total soil N were similar to those of total C. The average total N in the 0-7.5 cm depth in the 5-yr rotation (1,700 kg ha^{-1}) was 1.4 times greater than that in the 2-yr rotation (1,300 kg ha^{-1}). The average amounts of total N in the 0-7.5 cm depth showed the following trend Manure (1,900) > NPKS (1,400) = NKS(-P) (1400) > Check (1200). The Manure treatment was approximately 1.4 times higher than the treatments without P, but the NPKS was only about 1.1 times larger than both the treatments without P. The magnitude of average total N in the 0-7.5, 7.5-15, 15-30 and 30-45 cm depths was 1500, 1400, 1200 and 1100 kg ha^{-1}. There were marked differences between the surface and subsurface depths. The amount of total N in the 0-7.5 cm depth was significantly higher than that in the 30-45 cm depth (Table 2.2). The total soil N in the NKS(-P) treatment was significantly higher than that in the NPKS and Check treatments in the 15-30 cm depths in both rotations.

The trends of total soil P were different from those of total C and total N. The average total P in the 0-7.5 cm depth of both rotations was 565 (5-yr) and 568 (2-yr) kg ha^{-1}. The averages for Manure, NPKS, NKS(-P) and Check treatments in the 0-7.5 cm were 630, 640, 500 and 510 kg ha^{-1}. The total soil P in treatments with P were 1.2 times higher than in those without P. The magnitude of average total P in the 0-7.5, 7.5-15, 15-30 and 30-45 cm depths was 570, 570, 1010 and 990 kg m^{-3}, respectively. The two sub-surface depths are approximately 1.7 times greater than the two surface depths. There

was a greater amount of total P in the 5-yr Check treatment in the 30-45 cm depth compared the other treatments of the 5-yr rotation.

Total soil C:N ratios were only significant with respect to depth. Overall the total soil C:N ratios were averaged around 10 for the 0-7.5 and 7.5-15 cm depths and were about 7.8 (5-yr rotation) and 6.8 (2-yr rotation) in the subsurface depths. The total soil N:P ratios revealed significant differences with respect to rotation, treatment and depth. The total soil N:P ratios for the surface depths ranged from 3.46-1.75 whereas the ratios for the sub-surface depths ranged between 1.79-1.19. The total soil C:P ratios were significantly different between rotations, treatments and depths. The average total soil C:P for the 5-yr rotation in the 0-7.5 cm depth was about 31.8 whereas the 2-yr rotation had an average of about 21.8. The NKS(-P) in the 0-7.5 cm depth had the second highest total soil C:P ratio (33.5 in the 5-yr and 23.3 in the 2-yr). The C:N in the 0-15 cm depth is approximately 1.2 greater than that of the 15-45 cm depth; the N:P is approximately 1.5 times higher; and the C:P is approximately 2.7 times higher (Table 2.3).

Macro-organic Matter (MOM) and its C, N and P Contents in the 0-7.5 and 7.5-15 soil depths.

Overall, the trends for MOM and its C, N and P contents were similar (Table 2.4). The magnitudes of MOM and its C, N and P contents in the 5-yr were significantly greater than those in the 2-yr rotation for both depths. However, the trends for treatments were different from those for total C, N and P. The MOM magnitude and its C, N, and P contents in 0-7.5 cm depth were significantly higher than in the 7.5-15 cm depth. The MOM C in the 0-7.5 cm depth ranged from 860 kg ha^{-1} in the 5-yr Manure treatment to 190 kg ha^{-1} for the 2-yr Check treatment. The ranges of MOM C in the 7.5-15 cm depths ranged from 580 kg ha^{-1} in the 5-yr Manure treatment to 39 kg ha^{-1} in the 2-yr NPKS treatment, with the third lowest being 68 kg ha^{-1} coming from the 2-yr NKS(-P) treatment. The MOM N in the 0-7.5 cm depth ranged from the 5-yr NKS(-P) (47 kg ha^{-1}) to the 2-yr Check treatment (6.9 kg ha^{-1}). The 7.5-15 cm MOM N averages ranged from the 5-yr Manure (29 kg ha^{-1}) to 2-yr NPKS 1.4 kg ha^{-1}. The MOM P had similar trends to MOM N. The MOM P in the 0-7.5 cm depth ranged from 7.8 kg ha^{-1} in the 5-yr Manure treatment to 1.0 kg ha^{-1} in the 2-yr Check treatment. The MOM P in the 7.5-15 cm depth

ranged from 8.5 kg ha^{-1} in the 5-yr Manure treatment to 0.38 kg ha^{-1} in the 2-yr NPKS treatment.

Overall, the C:N of MOM in the 5-yr rotation 0-7.5 cm depth (24) was narrower than that in the 2-yr rotation (28) (Table 2.5). The Manure treatments in both rotations had the lowest MOM C:N ratios compared to other treatments. The MOM C:N ratio in the 0-7.5 cm ranged between 21 and 22 in the 2-yr and 5-yr Manure treatments compared to 35 in the NKS(-P) of the 2-yr rotation. The MOM C:N ratio widened with depth and was significantly wider in the 2-yr rotation than the 5-yr rotation . The MOM C:N ratio in treatments without P had were significantly wider than in those treatments with P in the lower depth.

The MOM N:P ratios were significantly different for rotations and depths but not for treatments. The MOM N:P ratio was around 5.0 in the 0.-7.5 cm depth but was wider in the 2-yr Check treatment (7.1). The 7.5-15 cm depths had narrower MOM N:P ratios ranging from 3.4 in the 2-yr and 5-yr Manure treatment to 4.4- 4.6 in the 2-yr and 5-yr NKS(-P) treatment. The MOM N:P ratios were significantly narrower in the 2-yr rotation and the values decreased with depth.

The MOM C:P ratios showed significant difference between rotation, treatment and depths. The MOM C:P ratios were significantly wider in the treatments without P and the ratios were significantly wider in the 2-yr rotation than those in the 5-yr rotation (Table 2.5). The MOM C:P ratios also decreased with depth in the 2-yr rotation treatments without P and increased in those same treatments with depth in the 5-yr rotation. The MOM C:P ratio in the Manure treatment narrowed dramatically while the Check and NKS(-P) widened with depth. The highest MOM C:P ratio in the 0-7.5 cm depths was in the 2-yr NKS(-P) and Check treatments (171 and 192, respectively) and the lowest in 7.5-15 cm depth was from the 5-yr and 2-yr rotation Manure treatments (67 and 80, respectively).

Short term indicators of SOM dynamics

The respired C trends showed significant differences between rotations, treatments and depths (Table 2.6). The average respired C for the 5-yr rotation for the 0-7.5 cm depth was 565 kg ha^{-1} and for the 2-yr rotation was 328 kg ha^{-1}. The Manure had the highest cumulative respired C (533 kg ha^{-1} for the 0-7.5 cm depth) while the Check treatment had the lowest cumulative respired C (369 kg ha^{-1} in the 0-7.5 cm depth). The average respired C in the 0-7.5 cm depth was 446 kg ha^{-1} compared to 292 kg ha^{-1} in the 7.5-15 cm depth. The 5-yr Manure treatment had 3-4 times as much respired C compared to the 2-yr Check for both depths.

Soil respiration was measured for the 0-7, 7-28, and 28-70 day intervals. The data are presented as cumulative C respired/interval (Fig. 2.1) and as average daily respiration rate as a proportion of total soil C (Fig 2.2). In the 5-yr rotation, the general trend for cumulative respiration in the 0-7.5 and 7.5-15 cm depths was Manure > NPKS = NKS(-P) > Check for all sampling periods (Fig. 2.1). In the 2-yr rotation, the general trend for cumulative respiration was Manure > NPKS = NKS(-P) = Check for the first two intervals for the 0-7.5 depth and for the last interval for the 7.5-15 cm depth (Fig. 2.1). There were no significant differences in the cumulative respiration for all treatments of the 2-yr rotation in the 7.5-15 cm depth for the first two sampling periods. The Manure treatment in the 5-yr rotation was approximately 1.5 times that in the Manure treatment in the 2-yr rotation (Fig 2.1). The differences were less pronounced with respect to the other treatments.

The average daily respiration in the 5-yr rotation was the greatest during the first 7 days of incubation in the 0-7.5 cm depth and declined significantly during the incubation period (Fig 2.2). Similar trends were also observed for the 7.5-15 cm depth except that the magnitude was lower. There was a somewhat irregular pattern in the 2-yr rotation in which the NKS(-P) treatment had a higher soil respiration than all the other treatments. This was more pronounced in the 0-7 day period (Fig 2.2). Apart from the 0-7 day period, the average daily respiration in the 2-yr NKS(-P) treatment was still lower than the 5-yr NKS(-P) treatment (Fig. 2.2).

The net N mineralized over 70 days exhibited similar trends to respired C (Table 2.6, Figure 2.3a). Rotation, treatment, and depth all contributed to significant differences between the net mineral N values. The 5-yr Manure treatment had the highest net N mineralization over 70 days in the 0-7.5 cm depth (66 kg ha^{-1}) while the 2-yr Check treatment had the lowest value (22 kg ha^{-1}). The 7.5-15 cm depth showed a similar trend but of a lower magnitude. The average daily N mineralization rates as a proportion of total N showed ranges of 4.3 - 0.9 % for the 5-yr Manure and 2-yr Check for the 0-7.5 cm depth and 2.99 - 0.87% for the same treatments for the 7.5-15 cm depth. The N mineralization rate was about 3-4 times higher in the 5-yr Manure treatment than the 2-yr Check treatment.

The magnitude of cumulative respired CO_2-C: Net mineral N ratios for the 0-7.5 cm depth was around 10-11 for the Manure treatments but increased to as much as 13.8 in the 2-yr NKS(-P) treatment. Significant differences were found in rotation, treatment and depth.

Microbial biomass C measured after 10 weeks incubation showed no specific patterns or trends except that the microbial C was significantly greater in the 0-7.5 cm depth than in the 7.5-15 cm depth, except for the 5-yr Manure and NPKS treatment, in which microbial biomass C significantly increased with depth (Table 2.6).

The ratio of CO_2-C evolved: microbial C was on average significantly higher in the 5-yr rotation (0-7.5 cm = 0.15 ; 7.5-15 cm = 0.091) than the 2-yr rotation (0-7.5 cm = 0.087; 7.5-15 cm = 0.050) (Table 2.6). In the 0-7.5 cm depth the NPKS, NKS(-P) and Check treatments were significantly lower than the Manure treatment. The averages for Manure, NPKS, NKS(-P) and Check treatments in the 0-7.5 cm were Manure (0.16); NPKS (0.11); NKS(-P) (0.10); and Check (0.11). There were also significant differences between the 0-7.5 cm (0.12) and 7.5-15 cm (0.071) depths.

Extractable P showed significant differences between rotation, treatment and depth. Extractable P in each treatment of the 5-yr rotation was significantly lower than that in the 2-yr rotation with the exception of NPKS, which showed no significant difference between the two rotations. The extractable P decreased significantly with depth but this

was more pronounced in the 2-yr rotation compared to the 5-yr rotation. In the 0-7.5 cm depth, the highest extractable P (44 kg ha^{-1}) was in the 2-yr Manure treatment and the lowest (1.6 kg ha^{-1}) was in the 5-yr NKS (-P) treatment (Table 2.6). The highest extractable P for the 7.5-15 cm depth was the 2-yr Manure treatment (22 kg ha^{-1}) and the lowest (1.5 kg ha^{-1}) was in the 5-yr NKS(-P) treatment. The extractable P significantly decreased with depth but was significantly higher in the treatments with P than those treatments without P. The extractable P in the NKS(-P) treatment was significantly lower than the Manure and NPKS treatments in both rotations (Table 2.6).

DISCUSSION

Impact of Soil P on Crop Yields

The amount of total soil C and N was significantly higher in the 5-yr rotation compared to the 2-yr rotation and decreased significantly with depth (Table 2.2). In contrast, the total soil P was not significantly different in the 5-yr rotation (790 kg ha^{-1}) compared to the 2-yr rotation (778 kg ha^{-1}). Total soil P significantly increased with depth. In this study, the organic P was not measured, however McKenzie et al. (1992) reported that 48% and 53% of total P in the limed and unlimed NPKS treatment of the 5-yr rotation, respectively, was in the form of organic P. If one assumes that 50% of total P in the these soils is organic, then the total organic P would also decreases with depth. This implies that there is a large reservoir of inorganic P in the 15-45 cm depths.

The total soil P in the Manure (630 kg ha^{-1}) and NPKS (650 kg ha^{-1}) treatments was significantly higher than the NKS(-P) (500 kg ha^{-1}) and Check (530 kg ha^{-1}) treatments in the 0-7.5 cm depth. The total soil P in treatments with P were 1.2 times higher than in those without P. The extractable P was also significantly higher in the treatments with P than those without P in the 0-7.5 and 7.5-15 cm soil depths. In the 0-7.5 cm depth, the highest extractable P (44 kg ha^{-1}) was in the 2-yr Manure treatment and the lowest (1.6 kg ha^{-1}) was in the 5-yr NKS (-P) treatment (Table 2.5). This trend was also observed in the 7.5-15 cm soil depth but the magnitude was lower.

As phosphorus is an essential element for plant growth and development and as plants get all their P from soil, a strong link between extractable P and crop yields would be

expected. The average grain and straw yields from 1972 to 1998 were greater in the 5-yr rotation than those in the 2-yr rotation. The average grain and straw yields in the 5-yr rotation were Manure > NPKS > NKS(-P) = Check while in the 2-yr rotation they were NPKS > Manure > NKS(-P) > Check (Table 2.1). The average grain and straw yields from the 5-yr rotation were 1.2 times higher than the yields of the 2-yr rotation. The yields in the Manure and NPKS treatments were about 1.7 times higher than those in the NKS(-P) and Check treatments. As the grain and straw yields in the Manure and NPKS treatments of the 5 yr-rotation were higher than those in the 2-yr rotation, a greater draw-down of extractable P would be expected in these treatments. This could be an explanation of a higher amount of extractable P in Manure and NPKS treatments of the 2-yr rotation compared to the 5-yr rotation (Table 2.6). McKenzie et al. (1992) reported a similar trend for NPKS and Check treatments of the 5-yr rotation.

N'Dayegamiye (1996) studied the effects of long-term (18 yr) applications of cattle manure (20 Mg ha^{-1} yr^{-1}) and NPK fertilizer on corn yields in a Le Bras loam (Humic Gleysol). The average yields of silage corn and wheat recorded from 1987 to 1991 were in the order of NPK + manure > manure = NPK > control (N'Dayegamiye 1996). Plant yields generally increase when nutrients are added to soils. Campbell et al. (1997) suggested that the synergistic effect of legumes in the 5-yr rotation, the manure and fertilizer applications, have produced higher yields of wheat in the 5-yr rotation compared to the 2-yr rotation at the Breton Plots. This observation is also valid for P applied as manure or inorganic fertilizer in the two rotations.

Impact of P on the MOM Fraction and Below Ground Carbon Inputs

The macro-organic matter (MOM) C is a portion of soil organic matter that is physically separated from the soil and consists mainly of straw particles, roots and root derived products (Bremer et al. 1994). In this study, the magnitudes of MOM and its C, N and P contents in the 5-yr were significantly higher than those in the 2-yr rotation, and were significantly higher in 0-7.5 cm depth than in the 7.5-15 cm depth. These results are consistent with observations of Bremer et al. (1994).

The MOM C in the 0-7.5 cm depth ranged from 860 kg ha^{-1} in the 5-yr Manure treatment to 190 kg ha^{-1} for the 2-yr Check treatment. In both depths, the MOM C:P ratios were similar in the 2-yr rotation (126) compared to those in the 5-yr rotation (119). These ratios in the treatments without P (146) were significantly wider those in treatments receiving P (100) (Table 2.5). In our study, we did not have the nutrient analyses of the grain and the straw, but the C:P ratios can be used as a substitute for nutrient content of the straw. The grain and straw yields of the Manure and NPKS treatments were higher than the NKS(-P) and Check treatments and the ratios of the MOM C:P were narrower in the former treatments compared to the latter. Bolinder et al. (1998) found that active fractions like microbial C, LF, and MOM C and N are more sensitive to short-term practice and environmental conditions than the total soil C and N. In Alfisols and Oxisols in Kenya, Marako et al. (1999) found that the significant trend of the magnitude of MOM mass and MOM P content was bare fallow soils < monocultures < native vegetation < Sesbania (an Agro-forestry crop in the tropics). Wander et al. (1994) and Janzen et al. (1992) found that soils in crop-rotations with a larger diversity of crops that included forages in contrast to monocultures and those receiving manure, have a higher average amount of MOM. The results of this study support the concept that the MOM fraction is a sensitive indicator of management practices.

Inputs of shoot and root C affects the amount of organic matter in the soil (Juma and McGill 1986). Izaurralde et al. (1993) measured root mass to a depth of 40 cm and reported that the root-straw ratio for barley grown at Breton was 0.25. Jenkinson and Rayner (1977) calculated that approximately 20% of C added as straw is transformed to stable OM over a period of 1-2 years. Using the above information, the amount of humified C produced every year can be calculated. The root inputs from the manure treatment of the 5-yr rotation (~4500 kg ha^{-1} straw yield x 0.25 root to shoot ratio x 0.20 humus formation per unit of C added) would produce approximately 225 kg ha^{-1} soil organic C (SOC) from barley alone per year. This will be different for wheat, oats, and forages (alfalfa and bromegrass). As there were significant differences in crop yields between rotations and treatments, differential amounts of humus will be formed every year. The differential rates of carbon inputs would lead to differences in soil organic matter in the long-term.

Impact of P on Microbial Activity and SOM Contents

The C respired, N mineralized, C respired: N mineralized ratio, and respired C per unit of microbial C, respired C per unit of soil total C, and mineralized N per unit of total soil N obtained from the laboratory incubation experiment were significantly higher in the 5-yr rotation compared to the 2-yr rotation and significantly decreased with soil depth (Table 2.6). The general trend for treatment effect for the above variables was Manure > NPKS ≥ NKS (-P) ≥ Check. The differences in specific mineralization rates for C and N per unit of microbial biomass and soil organic matter suggests that differences in the quality of microbial biomass and soil organic matter has developed in response to crop rotation and soil management. It is generally assumed that quantitative differences in organic matter lead to quantitative differences in soil respiration and carbon mineralization. The majority of the labile C was mineralized in the first week of the 10 week incubation. Consequently, less carbon was available to microorganisms for subsequent growth. This may explain why the microbial C was not significantly different between treatments, nor rotations; however, the ratio of respired C to microbial C paralleled the respired C in these soils. A specific respiration ratio is a better indicator of soil microbial activity because it measures the proportion of the soil microbial population that is in a dormant state (Anderson and Domsch 1990). Our results suggest that the quality of soil organisms and soil organic matter has to be incorporated into simulation models and in calculations of C sequestration in soil.

The major discoveries at the Breton Classical Plots with respect to C and N dynamics in the two crop rotations are: (1) The soil organic C (SOC) in the Manure treatment of the 5-yr rotation after 51 years of cultivation (1939-1990) was 25 Mg ha^{-1} more than the Check in the 2-yr rotation (Izaurralde et al. 2001); and (2) Soil organic C declined over a period of 70 years (1930-2000) at the rate of 14 and 7 g C m^{-2} y^{-1} in the 0.15 m depth of the Check and NPKS treatments of the 2-yr rotation; increased by 7 g C m^{-2} y^{-1} in the Manure treatment of the 2-yr rotation; and increased by 4, 14, and 28 g C m^{-2} y^{-1} in the Check, NPKS and Manure treatments of the 5-yr rotation (Grant et al. 2001). In this study the NKS(-P) treatment was significantly higher than the Check, yet significantly

lower than the NPKS treatment in the 5-yr rotation and was similar to the NPKS treatment (7.5-15 and 15-30 cm) in the 2-yr. The trends of total N were similar to those for total C. Total N may be higher in the 5-yr rotation due to belowground inputs of N by N fixing legumes (like alfalfa) and non-leguminous forages (like bromegrass).

The impact of P on soil C in the two rotations can be clearly seen from the trend of soil C:P ratios. The total soil C:P ratios were significantly different between rotations, treatments and depths. The average total soil C:P for the 5-yr rotation in the 0-7.5 cm depth (31.8) was significantly higher than in the 2-yr rotation (21.8). The narrow ratio of the total C: P ratio in the 2-yr wheat-fallow rotation may be due to lower C inputs compared to the 5-yr wheat, oat, barley, forage, forage rotation. The treatment effects could not be discerned from the total soil C:P ratios but the MOM C:P ratios were wider in treatments without P compared to those with P. More information is needed about forms of inorganic and organic P to identify relationships about organic C and P in different treatments of the two rotations.

Conclusions

This study added a new dimension to studies of the soil organic matter dynamics in the long-term Breton Classical Plots by introducing the NKS(-P) treatment. The total soil P, extractable P, and grain and straw yields in treatments with P were significantly higher than in those without P in both rotations. Since belowground C inputs are correlated to straw yields, differential amounts of C are added belowground by crops in the two rotations. Thus, the amount of total soil C and N is higher in the 5-yr compared to the 2-yr rotation, and the amounts among treatments followed the following trend: Manure > NPKS > NKS(-P) > Check.

The C respired, N mineralized, C respired: N mineralized ratio, and respired C per unit of microbial C, respired C per unit of soil total C, and mineralized N per unit of total soil N obtained from the laboratory incubation experiment were significantly higher in the 5-yr rotation compared to the 2-yr rotation and significantly decreased with soil depth. The general trend for treatment effect for the above variables was Manure > NPKS ≥ NKS (-P) ≥ Check. These results suggest that there is a qualitative difference in

microbial biomass and or soil organic matter. However, more studies are needed to confirm this idea.

Future Research

The total nutrient budget for the different treatments in the two rotations could not be done because only dry matter for yields has been recorded. Plant, manure and soil samples have been archived but have not been analyzed due to financial constraints. Therefore, there is a need to analyze the archived samples as well as use more sophisticated methods to study the dynamics of soil organic matter, especially P.

Table 2.1 Average grain and straw yields of spring wheat from 1972- 1998 from the 2-yr and 5-yr Rotations at the Breton Classical Plots in Breton, Alberta.

Rotation	*Treatment*	*Grain (kg ha^{-1})*	*Straw (kg ha^{-1})*
5-yr	Manure	2920a	4532a
	NPKS	2563b	4030b
	NKS(-P)	1625d	2559d
	Check	1623d	2490d
2-yr	Manure	2082c	3231c
	NPKS	2465b	3736b
	NKS(-P)	1742d	2658d
	Check	820e	1320e

Summary of ANOVA

Source of Variation	df	grain	straw
Rotation	1	***	***
Treatment	3	***	***
Rotation x Treatment	3	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Grain = 370, Straw = 455

Table 2.2 Total C, N, P contents in soils at four depths from two crop rotations at the Breton Plots

Rotation	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*pH*	*Total C kg C ha^{-1}*	*Total N kg N ha^{-1}*	*Total P kg P ha^{-1}*
5-yr	Manure	0- 7.5	1.2a	5.7a	22 400a	2 080a	590f
		7.5-15	1.3b	5.6a	20 600b	1 440e	670g
		15- 30	1.4c	5.6a	17 300c	1 890b	1 070b
		30- 45	1.5d	5.3b	10 700g	1 430e	1 000b
	NPKS	0- 7.5	1.3b	5.3c	18 500b	1 750b	650g
		7.5-15	1.4c	5.5b	15 900d	1 550d	620h
		15- 30	1.5d	5.5b	13 700e	1 620c	1 020b
		30- 45	1.5d	5.2c	10 100g	1 380d	980c
	NKS(-P)	0- 7.5	1.3b	5.2c	17 300c	1 650c	520j
		7.5-15	1.3b	5.2c	14 100e	1 340f	500j
		15-30	1.5d	5.4b	14 000e	1 700c	950d
		30-45	1.5d	5.2c	9 200g	1 280g	920d
	Check	0- 7.5	1.3b	5.4b	15 400d	1 360f	500j
		7.5-15	1.4c	5.3c	13 400e	1 360f	570i
		15-30	1.5d	5.3c	13 200e	1 640c	1 040b
		30-45	1.5d	5.1d	8 400h	1 250g	1 050b
2-yr	Manure	0- 7.5	1.2a	5.9a	18 500b	1 730b	660g
		7.5-15	1.5d	5.9a	14 900d	1 490d	650g
		15- 30	1.4c	5.8a	9 900g	1 380e	1 230a
		30- 45	1.5d	5.6b	9 300g	1 530d	1 140a
	NPKS	0- 7.5	1.2a	5.5b	10 400g	1 080i	620h
		7.5-15	1.5d	5.5b	9 500g	1 050i	600h
		15- 30	1.5d	5.9a	9 400g	1 340f	1 080a
		30- 45	1.5d	5.5b	9 300h	1 470d	1 110a
	NKS(-P)	0- 7.5	1.4c	5.3c	11 200f	1 200g	480k
		7.5-15	1.5d	5.4b	10 300g	1 130h	500j
		15-30	1.5d	6.1a	10 500g	1 490d	890e
		30-45	1.5d	6.0a	8 400h	1 220g	890e
	Check	0- 7.5	1.3b	5.5b	9 800g	1 010h	510j
		7.5-15	1.4c	5.5b	8 700h	940i	470k
		15-30	1.5d	5.6b	9 400g	1 290g	800f
		30-45	1.5d	5.4b	8 400h	1 340f	810f

Summary of ANOVA

Source of Variation	df	D_b	pH	Total C	Total N	Total P
Rotation	1	*	***	***	***	*
Treatment	3	*	*	***	***	***
Rotation x Treatment	3	NS	NS	NS	NS	**
Depth	3	***	NS	***	***	***
Rotation x Depth	3	**	NS	***	***	NS
Treatment x Depth	9	NS	NS	***	***	NS
Rotation x Treatment x Depth	9	NS	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Bulk Density = 0.029; pH = Total C = 119; Total N = 70; Total P = 20 *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 2.3 Total C, N, P ratios in soils at four depths from two crop rotations at the Breton Plots

Rotation	*Treatment*	*Depth (cm)*	*D_b (g cm^{-3})*	*C:N*	*N:P*	*C:P*	*C:*	*N:*	*P*
5-yr	Manure	0- 7.5	1.2	10.8a	3.46a	37.3a	10.8	1	0.29
		7.5-15	1.3	10.6a	2.90a	30.8b	10.6	1	0.34
		15- 30	1.4	9.12b	1.77c	16.2f	9.12	1	0.56
		30- 45	1.5	7.48d	1.42d	10.6g	7.48	1	0.70
	NPKS	0- 7.5	1.3	10.6a	2.62b	27.8b	10.6	1	0.38
		7.5-15	1.4	10.2a	2.49b	25.5c	10.2	1	0.40
		15- 30	1.5	8.47c	1.59d	13.5f	8.47	1	0.63
		30- 45	1.5	7.30d	1.42d	10.3g	7.30	1	0.70
	NKS(-P)	0- 7.5	1.3	10.5a	3.19a	33.5a	10.5	1	0.31
		7.5-15	1.3	10.5a	2.71b	28.5b	10.5	1	0.37
		15-30	1.5	8.26c	1.79c	14.8f	8.26	1	0.56
		30-45	1.5	7.22d	1.39d	10.1g	7.22	1	0.72
	Check	0- 7.5	1.3	10.4a	2.74b	28.5b	10.4	1	0.36
		7.5-15	1.4	9.89b	2.38b	23.6d	9.89	1	0.42
		15-30	1.5	8.05d	1.60d	12.9f	8.05	1	0.63
		30-45	1.5	6.75e	1.19d	8.00g	6.75	1	0.84
2-yr	Manure	0- 7.5	1.2	10.7a	2.88a	28.1b	10.7	1	0.35
		7.5-15	1.5	9.94b	2.31b	23.0d	9.94	1	0.43
		15- 30	1.4	7.16d	1.12d	8.03g	7.16	1	0.89
		30- 45	1.5	6.08e	1.34d	8.16g	6.08	1	0.75
	NPKS	0- 7.5	1.2	9.58b	1.73c	16.6f	9.58	1	0.58
		7.5-15	1.5	9.00c	1.75c	15.8f	9.00	1	0.57
		15- 30	1.5	7.07d	1.24d	8.74g	7.07	1	0.81
		30- 45	1.5	6.33e	1.32d	8.38g	6.33	1	0.76
	NKS(-P)	0- 7.5	1.4	9.31b	2.50b	23.3d	9.31	1	0.40
		7.5-15	1.5	9.13b	2.27b	20.8e	9.13	1	0.44
		15-30	1.5	7.10d	1.68c	11.9g	7.10	1	0.60
		30-45	1.5	6.89e	1.37d	9.46g	6.89	1	0.73
	Check	0- 7.5	1.3	9.78b	1.97c	19.3e	9.78	1	0.51
		7.5-15	1.4	9.28b	1.98c	18.4e	9.28	1	0.51
		15-30	1.5	7.26d	1.62c	11.8g	7.26	1	0.62
		30-45	1.5	6.31e	1.65c	10.4g	6.31	1	0.61

Summary of ANOVA

Source of Variation	df	Bulk Density	C:N	N:P	C:P
Rotation	1	*	NS	*	***
Treatment	3	*	NS	**	**
Rotation x Treatment	3	NS	NS	NS	NS
Depth	3	***	***	***	***
Rotation x Depth	3	**	NS	NS	NS
Treatment x Depth	9	NS	NS	NS	NS
Rotation x Treatment x Depth	9	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD:C:N = 0.77; N:P = 0.6; C:P = 3.7; *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 2.4 MOM C, N, P contents in MOM at two depths from two crop rotations at the Breton Plots

Rotation	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*MOM kg ha^{-1}*	*MOM C kg ha^{-1}*	*MOM N kg ha^{-1}*	*MOM P kg ha^{-1}*
5-yr	Manure	0- 7.5	1.2	2 440b	860b	39b	7.8a
		7.5-15	1.3	1 390d	580c	29c	8.5a
	NPKS	0- 7.5	1.3	2 000c	530c	23c	4.8c
		7.5-15	1.4	900e	330d	12d	2.8e
	NKS(-P)	0- 7.5	1.3	3 090a	1140a	47a	8.4a
		7.5-15	1.3	1 320d	550c	17d	3.7d
	Check	0- 7.5	1.3	1 980c	840b	34b	6.7b
		7.5-15	1.4	890e	370d	13d	2.8e
2-yr	Manure	0- 7.5	1.2	1 720c	580c	27c	6.2b
		7.5-15	1.5	300f	90f	3.8f	1.1e
	NPKS	0- 7.5	1.2	1 000d	280d	9.9e	2.4e
		7.5-15	1.5	160f	39f	1.4f	0.38e
	NKS(-P)	0- 7.5	1.4	1 200d	400d	11e	2.3e
		7.5-15	1.5	300f	75f	2.6f	0.60e
	Check	0- 7.5	1.3	610k	190e	6.9e	0.98e
		7.5-15	1.4	200f	68f	2.0f	0.53e

Summary of ANOVA

Source of variation	df	MOM	MOM C	MOM N	MOM P
Rotation	1	***	***	***	***
Treatment	3	*	*	*	*
Rotation x Treatment	3	NS	NS	NS	NS
Depth	1	**	***	***	***
Rotation x Depth	1	NS	NS	NS	NS
Treatment x Depth	3	NS	NS	NS	NS
Rotation x Treatment x Depth	3	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: MOM = 410 MOM C = 198; MOM N = 9.32; MOM P = 2.64 . *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant

Table 2.5 MOM C, N, P Ratios in MOM at two depths from two crop rotations at the Breton Plots

Rotation	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*MOM kg ha^{-1}*	*C:N*	*N:P*	*C: P*	*C:*	*N:*	*P*
5-yr	Manure	0- 7.5	1.2	2 440b	22a	5.0c	111c	22	1	0.20
		7.5-15	1.3	1 390d	20a	3.4a	67.2a	20	1	0.30
	NPKS	0- 7.5	1.3	2 000c	24b	4.7b	111c	24	1	0.21
		7.5-15	1.4	900e	27b	4.2b	115c	27	1	0.24
	NKS(-P)	0- 7.5	1.3	3 090a	25b	5.6c	138d	25	1	0.18
		7.5-15	1.3	1 320d	33d	4.6b	151e	33	1	0.22
	Check	0- 7.5	1.3	1 980c	25b	5.1c	126d	25	1	0.20
		7.5-15	1.4	890e	29c	4.5b	132d	29	1	0.22
2-yr	Manure	0- 7.5	1.2	1 720c	21a	4.4b	93.9b	21	1	0.23
		7.5-15	1.5	300f	24b	3.4a	80.0b	24	1	0.29
	NPKS	0- 7.5	1.2	1 000d	28c	4.1b	116c	28	1	0.25
		7.5-15	1.5	160f	28c	3.6a	104b	28	1	0.28
	NKS(-P)	0- 7.5	1.4	1 200d	35d	4.8c	171f	35	1	0.21
		7.5-15	1.5	300f	29c	4.4b	125d	29	1	0.23
	Check	0- 7.5	1.3	610k	27b	7.1d	192g	27	1	0.14
		7.5-15	1.4	200f	33d	3.9a	129d	33	1	0.26

Summary of ANOVA

Source of variation	df	D_b	MOM C:N	MOM N:P	MOM C:P
Rotation	1	*	***	***	***
Treatment	3	*	*	NS	***
Rotation x Treatment	3	NS	NS	NS	***
Depth	1	***	***	***	***
Rotation x Depth	1	**	***	***	***
Treatment x Depth	3	NS	*	NS	NS
Rotation x Treatment x Depth	3	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: MOM C:N = 2.0; MOM N:P = 0.8; MOM C:P = 14 . *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant

Table 2.6 Short- Term Indicators of soil C,N,P mineralized over 70 days including two depths from two crop rotations at the Breton Plots

Rotation	*Treatment*	*Depth (cm)*	*Resp C[a] kg C ha^{-1}*	*Net N Min[b] kg N ha^{-1}*	*CO_2-C: N_{min}*	*Micro C[c] kg C ha^{-1}*	*Resp C: Micro C*	*Extract P[d] kg P ha^{-1}*
5-yr	Manure	0- 7.5	648a	66a	9.8b	4 320d	0.20a	23.9b
		7.5-15	445c	41c	10.8c	5 320c	0.11b	6.8c
	NPKS	0- 7.5	565b	48b	11.8d	5 320c	0.14b	19.4b
		7.5-15	324d	26d	12.3d	5 960b	0.072c	5.0c
	NKS(-P)	0- 7.5	530b	44b	12.2d	6 440a	0.11b	1.6f
		7.5-15	316d	29d	10.9c	5 200c	0.081c	1.5f
	Check	0- 7.5	518b	43b	12.1d	4 880c	0.14b	2.6e
		7.5-15	278e	22e	12.8e	3 720e	0.10c	2.0e
2-yr	Manure	0- 7.5	419c	45b	9.3b	5 000c	0.11b	43.8a
		7.5-15	158f	31d	5.0a	4 040d	0.052d	22.7b
	NPKS	0- 7.5	323d	30d	10.6c	6 080b	0.071c	21.3b
		7.5-15	104f	11f	9.4b	3 160f	0.044d	9.5c
	NKS(-P)	0- 7.5	348d	25d	13.8f	5 040c	0.092c	3.8d
		7.5-15	158f	13f	12.2e	3 920e	0.054d	2.9e
	Check	0- 7.5	220e	22e	9.9b	4 000d	0.073c	4.7d
		7.5-15	105f	15f	6.8a	2 840f	0.049d	3.5d

Summary of ANOVA

Source of Variation	df	Resp C	Net Min	N C_{min}: N_{min}	Micro C	Resp C: Micro C	Extract P
Rotation	1	***	***	***	NS	**	***
Treatment	3	***	***	***	NS	***	***
Rotation x Treatment	3	NS	NS	NS	NS	NS	***
Depth	2	***	***	***	*	**	***
Rotation x Depth	1	NS	NS	NS	NS	NS	***
Treatment x Depth	3	NS	NS	NS	NS	NS	***
Rotation x Treatment x Depth	3	NS	NS	NS	NS	NS	NS

a = Respired Cumulative CO_2-C
b = Net Mineral N
c = Microbial C
d = Extractable P (day 0)

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Respired C = 78.19; Mineral N = 8.93; C_{min}: N_{min} = 0.8 ; Micro C = 346; Extractable P = 3.91; *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

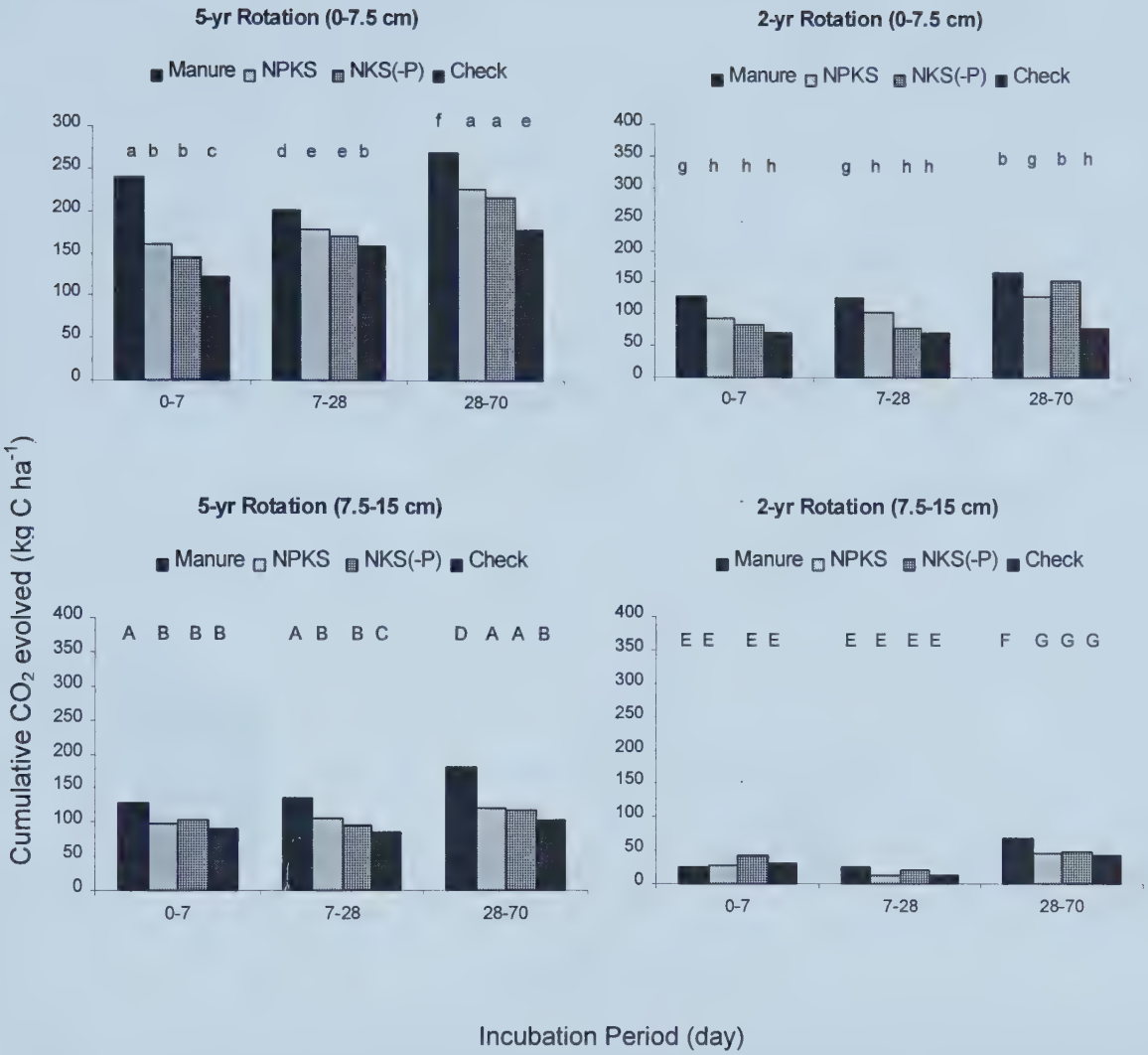

Fig. 2.1 Non-Cumulative CO_2 evolved at specific time intervals from soil samples taken and incubated for 10 weeks from the 5-yr and 2-yr rotations at the Breton Plots. LSD: 0-7.5 cm = 32; 7.5- 15 cm = 27. Bars displaying the same letter are not significantly different (P>0.05).

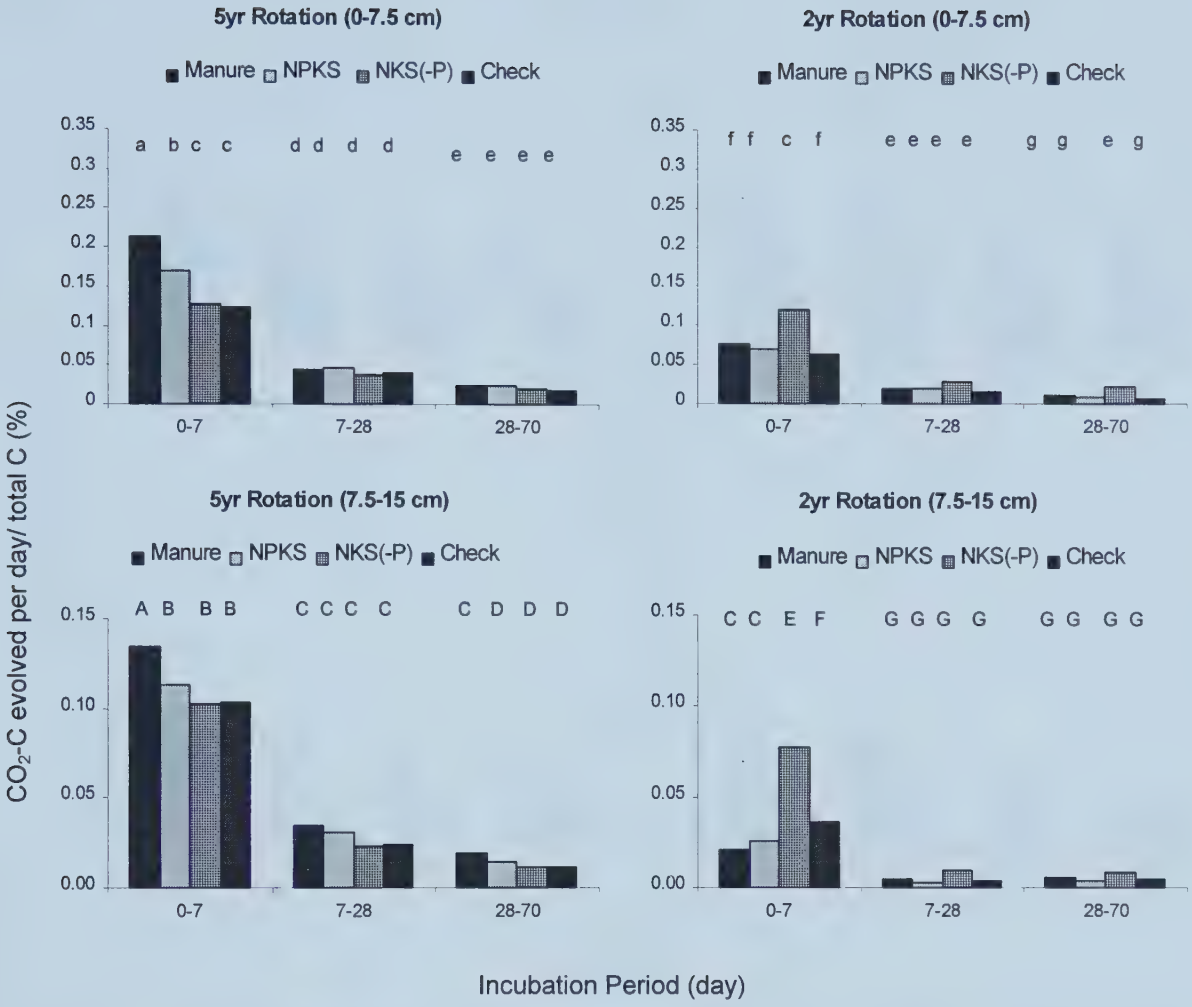

Fig. 2.2. Soil respiration expressed as a percentage of total C (CO_2-C at specific time intervals/ total C/ time x 100) for specific time periods in soil samples taken and incubated for 10 weeks from the 2-yr and 5-yr rotations at the Breton Plots; LSD: 0-7.5 cm = 0.014; 7.5-15 cm = 0.016. Bars displaying the same letter are not significantly different (P>0.05).

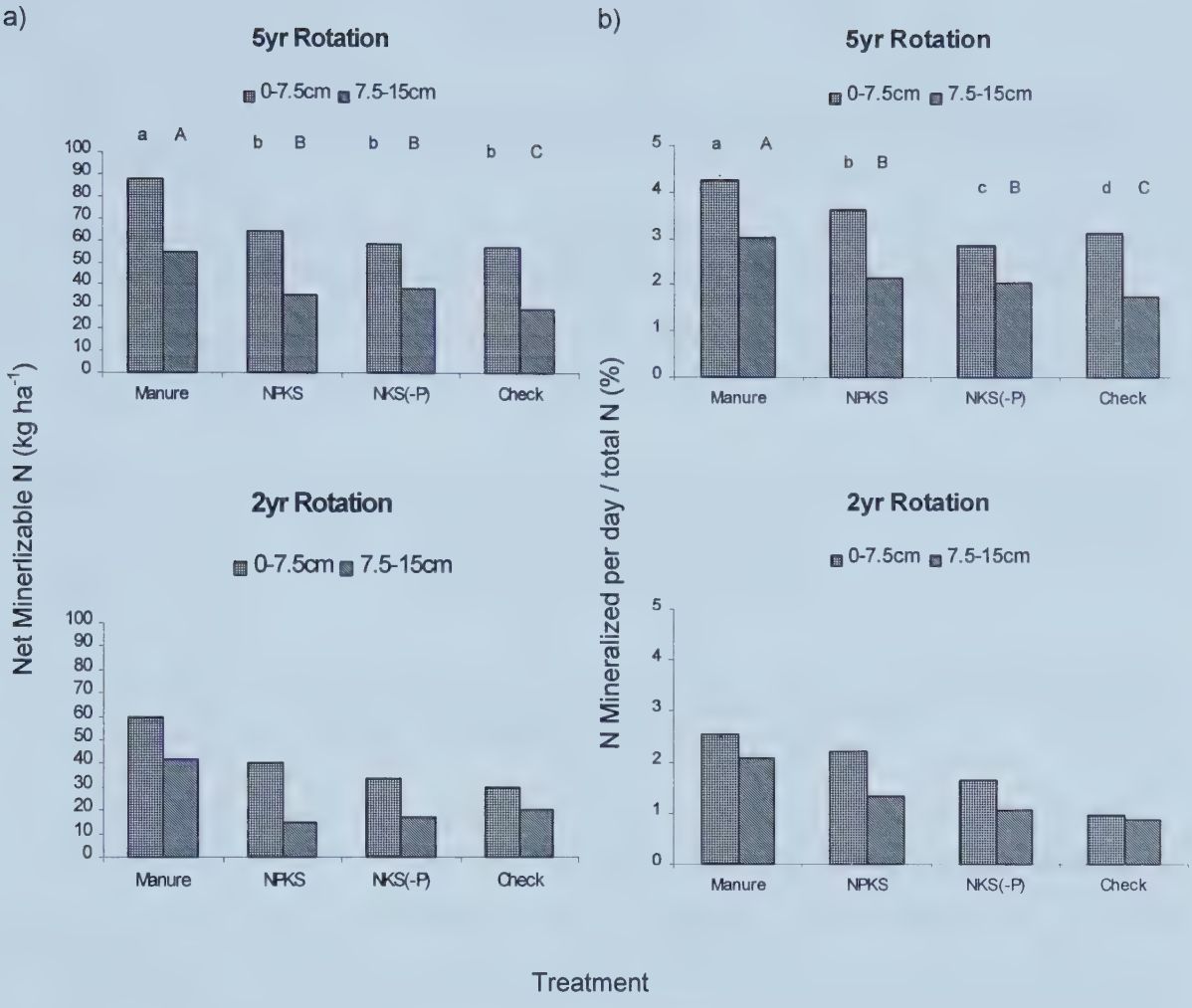

Fig. 2.3 (a) Net Mineralizable N and (b) Net N mineralization rate expressed as a percentage of total N (net mineralizable N/ total N x 100) for 70 days incubation weeks of soil samples taken from the 2-yr and 5-yr rotations at the Breton Plots; LSD: Net Mineralizable N = 8.9 Total N mineralized = 0.008. Bars displaying the same letter are not significantly different (P>0.05).

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Chapter 3. Impact of Lime and Phosphorus on Soil Organic Matter Dynamics in the 5-yr Long-term, Crop Rotation at Breton, Alberta

INTRODUCTION

Soil acidity originates from several sources: humus, aluminosilicate clays, hydrous oxides of iron and aluminum, soluble salts and carbon dioxide. It increases due to: (1) the use of commercial inorganic ammoniacal fertilizers which produce H^+ ions during nitrification; (2) crop removal of basic cations (calcium, magnesium, potassium, sodium and ammonium) in exchange for H^+; (3) leaching of these cations being replaced by H^+ and subsequently by Al^{3+}; and (4) decomposition of organic residues leading to the formation of carbonic acid and other inorganic acids (Tisdale et al. 1993).

Soil acidity controls the availability of P. Plant available P is optimum between pH 6 and 7 because inorganic P is precipitated as iron and aluminium phosphates at pH 5.5 and below, and as calcium phosphates at pH above 7.5 (Tisdale et al. 1993).

Gray Luvisolic soils in the Canadian Prairies tend to have deficiencies in soil N and S. Therefore, application of mineral or organic fertilizers provide a significant positive response in cereal and grass forage crops (Penney et al. 1990; Harapiak et al. 1992). However, acidification may adversely affect the soil chemical properties of cultivated soils (Mahli et al. 1998). Nyborg and Hoyt (1978) have shown, under laboratory and field conditions, that soil acidity does not restrict mineralization of N, although liming temporarily increases the mineralization of N (Black 1968). Soil acidity restricts nitrification (Harmsen and van Schrevan 1955; Nyborg and Hoyt 1978). Liming acid soils to the optimal pH of 6.5 to 7.0 increases the availability of N and P (Troeh and Thompson 1993).

Liming is a well known agronomic practice because it increases yields of a number of crops. Liming trials conducted at 28 sites in the western Great Plains of Canada for barley, canola, red clover and alfalfa showed average yield increases of 82, 89, 87 and 54%, over the unlimed respectively (Hoyt and Nyborg 1987). Soil acidity causes toxicity or nutritional problems for alfalfa at pH < 6 and for barley at pH < 5.5 (Elliott et al. 1973). Forage and nitrogen fixing crops such as red clover are acid tolerant when

compared to alfalfa. However, these crops perform at their optimum over pH 6.5 (Nyborg et al. 1970). Acid-tolerant crops may prevent yield losses due to soil acidity, however this limits the choice of crops that may be grown and may pose an extra demand for fertilizers because of decreased nutrient availability in acid soils (Mahli et al. 1995).

The trends of crop yields and soil organic matter in the Check, Manure and NPKS treatments of the 2-yr and 5-yr rotations of the Breton Classical Plots have been developed using data for the unlimed plots of 5-yr rotation, and the unlimed plots of the 2-yr rotation till 1972, and the limed plots of the 2-yr rotation from 1972 onwards (Izaurralde et al. 1995, 2001; Juma et al. 1997; Grant et al. 2001). This study focuses on crop yields, soil organic matter, and short-term indicators on the limed and unlimed portions of the 5-yr rotation. The objectives of this study were to assess the impact of liming and phosphorus on crop yields and dynamics of soil organic matter in four treatments (Manure, NPKS, NKS(-P) and Check) of the 5-yr long-term rotation at Breton.

MATERIALS AND METHODS

Cropping and Liming History

The 5-yr cereal forage rotation on the Breton Classical Plots consists of wheat, oat, barley, forage, forage. The forage crops have varied over time: sweet clover and red clover or alfalfa and red clover from 1930 to 1955; alfalfa, red clover, timothy, creeping red fescue and bromegrass from 1956 to 1963; alfalfa, red clover, creeping red fescue and bromegrass between 1964 to 1966; and alfalfa and bromegrass from 1967 onwards. Out of the 11 treatment plots in this rotation, four get applications of inorganic nitrogen fertilizer in the form of ammonium sulfate (21-0-0) or ammonium phosphate (16-20-0). The yields of crops in NPKS plots showed an erratic trend and tended to decline over a period of 40 years (1930-1970), especially from 1965 to 1970. Robertson and McGill (1983) attributed the decline in yields of perennial forages in the Gray Luvisolic soil at Breton to increase in acidity due to applications of ammoniacal fertilizers and change in forage crops from more complex mixtures in earlier years to alfalfa and bromegrass from 1967 onwards. As alfalfa is less tolerant of soil acidity than red clover, the plots were

split and the east half of the 5-yr rotation plots (Series A-D and F) and complete plots of the 2-yr rotation (Series E) were limed to pH 6.5 in 1972 if the pH had dropped to ≤ 6.

Sampling

Soil samples were collected from the east (limed) and west sides (non-limed) of the Check, NPKS, Manure, and NKS(-P) treatments (plots 1, 2, 3, and 4) in Series A, B, C, D, and F of the 5 yr rotation in October 1998. A coring truck with a steel coring tube of 50.8 cm length and 7.6 cm diameter was used. Three cores were taken from each side of the half-plot and divided into 0-7.5 cm, 7.5- 15 cm, 15- 30 cm, and 30- 40 cm depths. The three soil cores from each half-plot were composited, air dried and measured for bulk density according to the protocol described by Ellert and Johnson (1997). Bulk density was calculated based on dry soil using the same protocol described in Chapter 2. The pH values were measured in 0.01 M $CaCl_2$ using the same protocol described in Chapter 2.

Measurements

The samples taken from the limed and unlimed half-plots of the 5-yr rotation were handled and analyzed using methods outlined in chapter 2. Total soil C, N, and P and extractable P were measured in these samples for all four depths. MOM C, N, and P; mineralized C and N (after 10 weeks incubation); and microbial C (after 10 weeks incubation) were measured in soil samples from the 0-7.5 and 7.5-15 cm depths.

Statistical Analysis

The General Linear Models Procedure of SAS (SAS Institute 1990) was used to analyse the experimental data. A three factor ANOVA in conjunction with Duncan's and Boneferroni's Multiple Range tests were used to test for the liming, treatment, and depth effects. The results are means of five replicates for both the limed and unlimed half-plots.

RESULTS

Spring wheat grain and straw yield trends from 1972- 1998 for all four treatments in the limed and unlimed halves of the 5-yr rotation

The grain yields were significantly higher in the limed compared to the unlimed plots (Table 3.1). The average grain yield in the limed plots (2521 kg ha^{-1}) was approximately 1.2 times higher than the unlimed plots (2093 kg ha^{-1}). The average yields of grain in the Manure (3212 kg ha^{-1}) and NPKS (2999 kg ha^{-1}) treatments were higher than those in the NKS(-P) (1634 kg ha^{-1}) and Check (1379 kg ha^{-1}) treatments. The grain yields were about 2.3 times higher for the Manure treatments compared to the Check treatments. Average straw yields for Manure, NPKS, NKS(-P) and Check treatment were 4190 kg ha^{-1}, 3901 kg ha^{-1}, 2550 kg ha^{-1}, 2154 kg ha^{-1}, respectively. The straw yields in the Manure treatment yields were 1.9 times greater than those in the Check.

Soil Bulk Density, pH, soil total C, N and P, and soil C:N:P ratios in the 0-7.5, 7.5-15, 15-30 and 30-45cm depths.

Soil bulk density was not significantly different between limed and unlimed plots in the 5-yr rotation, but there were significant differences for treatments and depth (Table 3.2). The bulk density ranged from 1.2-1.4 g cm^{-3} in the surface depths (0-7.5 cm and 7.5-15 cm). Subsurface depths (15-30 cm and 30-45 cm) had bulk densities ranging from 1.4-1.5 g cm^{-3}. The average bulk densities were 1.25, 1.36, 1.49 and 1.51 g cm^{-3} in 0-7.5, 7.5-15, 15-30 an 30-45 cm depths, respectively. Overall, the Manure treatments had the lowest bulk densities in all depths (1.2, 1.35, 1.45, 1.5 g cm^{-3} for the 0-7.5, 7.5-15, 15-30 an 30-45 cm depths, respectively). The NPKS treatment had similar bulk densities between both half-plots except for the 0-7.5 cm in which the limed plots had a higher bulk density (1.3 g cm^{-3}) than the unlimed plots (1.2 g cm^{-3}). The average bulk density in the 0-7.5 cm depth of the NKS(-P) and Check treatments was 1.3 and 1.25 g cm^{-3}, respectively.

Most of the pH values for both the limed and unlimed halves values were moderately to strongly acidic (4.4-5.5) (Table 3.2). The average pH values for the four depths for the limed Manure, NPKS, NKS(-P) and Check plots were 5.6, 5.4, 5.3 and 5.3, respectively. The average pH values for all four depths for the unlimed Manure, NPKS, NKS(-P) and

Check plots were 5.3, 4.7, 4.9 and 5.0, respectively. Thus, on average, the pH values in the limed treatment plots were at least 0.2 units higher than in the unlimed treatments and in the case of the NPKS treatment this difference is almost 0.7 units. The differences of pH values were more pronounced among the limed and unlimed halves of the NPKS, NKS(-P), and Check treatments. The limed Manure treatment was the only treatment that had an average pH over 5.5 for all four depths.

Total C values were not significantly different between limed and unlimed plots yet there were significant differences for treatments and depth (Table 3.2). The trends for total soil C were similar for all depths, therefore the focus will be on the 0-7.5 cm depth. The total soil C in the NPKS (18, 200 kg ha^{-1}) and NKS(-P) (17, 400 kg ha^{-1}) treatments were significantly lower than the Manure (22, 400 kg ha^{-1}) treatment but significantly higher than the Check (14, 700 kg ha^{-1}). The average total C for the four depths across limed and unlimed halves are the following: 18, 200; 15, 600; 13, 700; and 10, 100 kg ha^{-1}, respectively. However, total soil C did not significantly decrease with depth between the 7.5-15 cm and the 15-30 cm depths in the NKS(-P) and Check treatments.

Total soil N values were not significantly different between limed and unlimed plots however the treatment and treatment x depth were significant (Table 3.2). In the 0-7.5 cm depth the average total N values for the Manure, NPKS, NKS(-P) and Check treatments were 2092, 1718, 1673, and 1425 kg ha^{-1}, respectively. The total soil N decreased in depth from 0-15 cm and then increased in the 15-30 cm depth for all treatments except the Manure treatment. The overall averages for total soil N by depths 0-7.5, 7.5-15, 15-30 and 30-45 cm were 1725, 1515, 1680 and 1350 kg ha^{-1}, respectively.

Total soil P values in the limed plots were significantly lower compared to the unlimed plots (Table 3.2). In most cases, the total soil P increased with depth. The average total soil P values in the 0-7.5 cm depth of the limed (565 kg ha^{-1}) treatment were significantly lower than that in the unlimed (595 kg ha^{-1}) treatment. The average values of total P for the Manure, NPKS, NKS(-P), and Check treatments in the 0-7.5 cm depth were 635, 650, 530 and 505 kg ha^{-1}, respectively. Total P average values in the 0-7.5, 7.5-15, 15.30, 30-45 cm depths were 580, 620, 1150 and 1100 kg ha^{-1}, respectively. The

total soil P in the unlimed Manure treatment was significantly higher compared to other unlimed and limed treatments. Total P increased in the two lower depths (15-30 cm and 30-45 cm) and the treatments without P, except for the limed Check were significantly lower than those with P. Total soil P decreased below the 15-30 cm depth in all limed treatments with the exception of the Check treatment (Table 3.2).

The total soil C:N ratios in the 0-7.5 and 7.5-15 cm depths were similar (~10) and were significantly higher than those in the 15-30 cm (8.0) and the 30-45 cm (6.9) depths (Table 3.3). The average total soil N:P ratio in limed plots (2.2) for all depths was significantly higher than that in the unlimed plots (2.0). The average total soil N:P ratios of the Manure, NPKS, NKS(-P) and Check treatments in the 0-7.5 cm depth were 3.3, 2.7, 3.2, and 2.8, respectively. The average total soil N:P ratios for the 0-7.5 cm, 7.5-15 cm, 15-30 cm and 30-45 cm depths were 3.0, 2.5, 1.5, and 1.3. The soil N:P ratios in unlimed Check treatment was significantly higher than the limed treatment but there were no significant differences between the limed and unlimed halves in other treatments. The soil N:P ratios in the Manure and NPKS treatments of the unlimed plots were significantly lower than the N:P of the limed halves of those treatments at depths below 15 cm.

The average total soil C:P ratios in the 0-7.5 cm depth ranged from 37.5 (limed Manure) to 27.6 (unlimed NPKS). The average total soil C:P ratios for the limed and unlimed plots in the 0-7.5 cm depth were 32.0 and 30.7, respectively. The average total soil C:P ratios in the Manure, NPKS, NKS(-P) and Check treatments in the 0-7.5 cm depth were 35.3, 28.0, 32.9, and 29.3, respectively. The average soil C:P ratios in the 0-7.5, 7.5-15, 15-30, and 30-45 cm were 31.4, 25.4, 12.5, and 9.1, respectively. The soil C:P ratios in the Manure and NPKS treatments of the unlimed plots were significantly lower than those of the limed halves at depths below 15 cm.

MOM C, N, P and MOM C:N:P in the 0-7.5 and 7.5-15 depths for the limed and unlimed halves of all treatments

The size and C, N and P content of the MOM fraction was significantly higher in the 0-7.5 cm depth compared to the 7.5-15.0 cm depth. The average MOM C, N and P ratios

for depths 0-7.5 cm and 7.5-15 cm were: 780 and 350 kg C ha^{-1}, 34 and 13 kg N ha^{-1} and 6.6 and 3.1 kg P ha^{-1} (Table 3.4).

The MOM C:N ratios in the 0-7.5 cm depths ranged from 18 for unlimed NKS(-P) to 29 for the unlimed Check treatment. In the 7.5-15 cm depth the MOM C:N ratio ranged from 20 to 33. The MOM C:N ratio in unlimed half-plots significantly increased with depth compared to the limed half-plots. The MOM C:N ratio significantly increased with depth in all treatments except limed Manure (Table 3.5).

The MOM N:P ratios the 0-7.5 cm depth ranged from 4.5 (unlimed NPKS) to 6.1 (unlimed Manure). The 7.5-15 cm depth had N:P values ranging from 3.4 (limed Manure) to 4.8 (unlimed NPKS). There was less variation between treatments at this depth. There was significant lime-treatment interaction in which MOM N:P ratios in treatments without P were significantly wider than those in treatments with P, but only in the limed half-plots (Table 3.5).

The MOM C:P ratios ranged from 138 (NKS(-P)) to 111 (Manure) in the limed halves and 146 (Manure) to 90.1 (NKS(-P)) in the unlimed halves in the 0-7.5 cm depth. The MOM C:P ratios were wider in the NKS(-P) and Check treatments of the limed half-plots compared to the Manure and NPKS treatments. The average MOM C:P values in the unlimed half-plots showed no significant difference between treatments with or without P (Table 3.5).

Short term indicators: Mineralized C and N, Extractable P, Microbial C, Mineralized C: Microbial C value

The average CO_2-C respired after 10 weeks incubation from soil samples obtained from the 0-7.5 cm depth of limed plots (566 kg C ha^{-1}) were significantly higher than from the unlimed half-plots (511 kg C ha^{-1}) (Table 3.6). Average respired C values between the Manure, NPKS, NKS(-P), and the Check treatments in the 0-7.5 cm depth were 610, 546, 552, and 445 kg C ha^{-1}. The average respired C in the 0-7.5 cm and the 7.5-15 cm depths were 538 and 284 kg C ha^{-1}, respectively. The amounts of CO_2-C respired after 10 weeks incubation in the Manure and NPKS treatments were generally higher than those in the NKS(-P) and the Check treatments in the limed plots (Table 3.6).

Respired CO_2-C from soil during specific time intervals was significantly higher in the limed compared to the unlimed half-plots; the Manure treatment had the highest respiration rate compared to other treatments (Fig. 3.1). There was less variation between treatments in the unlimed plots. For the unlimed treatments in the 7-28 and 28-70 day intervals the NKS(-P) treatment had a respired CO_2-C of approximately 170 kg C ha^{-1} (Fig. 3.1).

The magnitude of the ratios of CO_2-C respired per day: total C in the limed plots for both depths showed the following trend: Manure > NPKS > NKS(-P) = Check for the 0-7 day period. These differences diminished in magnitude for the 7-28 and 28-70 day intervals (Fig. 3.2). The magnitude of the ratios of CO_2-C respired per day: total C in the unlimed plots for both depths showed the following trend: NKS(-P) > Manure > NPKS > Check for the 0-7 day period. These differences diminished in magnitude for the 7-28 and 28-70 day intervals (Fig. 3.2).

The amount of net mineral N after 10 weeks incubation showed significant differences between treatments and depths but not between limed (50 kg N ha^{-1}) and unlimed (51 kg N ha^{-1}) plots (Table 3.6, Figure 3.3). The average net mineral N for the Manure, NPKS, NKS(-P) and Check treatments in the 0-7.5 cm depths were 67, 50, 45, and 42 kg N ha^{-1}, respectively. The average net mineral N in the 0-7.5 cm depth (51 kg N ha^{-1}) was significantly higher than that in the 7.5-15 cm depth (29 kg N ha^{-1}). Mineralized N per day/total N was significantly higher in the limed (3.5%) compared to the unlimed (1.5%) plots. The mineralized N per day/total N was the lowest in the NKS(-P) unlimed treatment (0.5%). In the limed half-plots in the 0-7.5 cm, the mineralized N per day/total N in the NKS(-P) was significantly lower than the NPKS and Manure treatments (Fig 3.3).

The average CO_2-C to net mineral N ratio in the 0-7.5 cm depth was significantly higher in limed (11.5) compared to the unlimed (10.1) plots (Table 3.6). The average CO_2-C to net mineral N ratios for the Manure, NPKS, NKS(-P) and Check treatments in the 0-7.5 cm depth were 9.2, 11.5, 12.4, and 10.7, respectively. The average CO_2-C to net mineral N ratio for the 0-7.5 cm and 7.5-15 cm depths were 10.8 and 10.0,

respectively. The unlimed Check and limed manure treatments had a significantly lower ratio than the limed Check treatment.

Microbial C exhibited significant differences for lime and depth but there were no significant differences between treatments (Table 3.6). The average microbial C values in the 0-7.5 cm depth for limed and unlimed treatments were 3930 and 4230 kg C ha^{-1}, respectively. Averages between the two depths were the following: 4590 kg C ha^{-1} in the 0-7.5 cm depth and 2990 kg C ha^{-1} in the 7.5-15 cm depth. Thus the microbial biomass was significantly higher in the 0-7.5 depths compared to the 7.5-15 depth with the exception of the limed Manure and NPKS treatments where the reverse is true.

The ratio of respired CO_2-C to Microbial C (Table 3.6) showed significant differences for lime, treatment and depth. The average ratio of Respired C to Microbial C in the 0-7.5 cm depth for limed (0.15) was significantly greater than that in the unlimed plots (0.12). For the treatments, the average ratios in the 0-7.5 cm depths for Manure, NPKS, NKS(-P), and Check were 0.15, 0.14, 0.13 and 0.12, respectively. The average respired C to microbial C ratio for the 0-7.5 cm and 7.5-15 cm depths were 0.13 and 0.097, respectively.

Extractable P measured at week 0 showed similar trends for both depths (Table 3.6). There were significant differences in lime, treatment and depth. The highest extractable P values came from the Manure and NPKS treatments of the unlimed plots in the 0-7.5 cm depth (20.0 and 36.9 kg P ha^{-1}). The overall average extractable P in the 0-7.5 cm depth of the limed plots (11.9 kg P ha^{-1}) was significantly lower than in the unlimed plots (15.8 kg P ha^{-1}). The average extractable P values for Manure, NPKS, NKS(-P), and Check plots in the 0-7.5 cm depth were 22.0, 28.1, 1.7 and 3.4 kg P ha^{-1}, respectively. The average extractable P values were 13.8 kg P ha^{-1} in the 0-7.5 cm depth and 5.0 kg P ha^{-1} in the 7.5-15 cm depth. The extractable P in the unlimed NPKS treatment was significantly higher than the limed NPKS and the limed and unlimed Manure treatments. The extractable P in both the NKS(-P) and Check treatments were significantly lower than the Manure and NPKS treatments both depths.

DISCUSSION

Liming, soil pH and the Availability of Phosphorus

Lime was applied to raise the pH to 6.5 in 1972 and a few times in the 1980's, but the pH declined because lime was not applied in the 1990's. In 1998, the pH of the surface horizons (0-15 cm) of the limed Manure treatment was between 5.6 and 5.7 compared to 5.3 in the unlimed Manure plots. Feedlot cattle manure contains 1.9% N, 0.7% P, 2.0% K, 1.3% Ca, 0.7% Mg and 0.5% S (Eghball and Power 1994) in addition to organic C. Manure and inorganic fertilizers were applied on N equivalent basis for the treatments in the 2-yr and 5-yr crop rotations. The addition of basic cations via manure helped to maintain a higher pH in the limed and unlimed manure treated plots. It is also possible the uptake rate of NH_4^+ was equal to the NH_4^+ mineralized from the manure, therefore less N was nitrified.

The pH in the unlimed NPKS and NKS(-P) was significantly lower than the unlimed Check treatment. This can be explained by the nitrification of ammoniacal inorganic fertilizer applications in these treatments (Nyborg et al. 1988, Heenan and Taylor 1995, Mahli et al. 1998). Similar trends were also observed for these treatments in the limed half-plots. The pH of surface soil horizons of limed half-plots of the above treatments was above 5 but it was below 5 in the unlimed half-plots. The pH values for all the plots are sub-optimal for any of the crops planted on these plots (wheat, barley, alfalfa, bromegrass) with the exception of oats, which are more acid tolerant (Elliott et al. 1973; Russell 1973). (reported in CaCl2??

Phosphorus is an essential nutrient for plant growth and development. Crops become stunted and spindly, and develop poor or no seed under P limiting conditions. The extractable P in the Manure (21.9 kg P ha^{-1}) and NPKS (28.1 kg P ha^{-1}) treatments was significantly higher than the NKS(-P) (1.7 kg P ha^{-1}) and Check treatments (3.4 kg P ha^{-1}). The average grain yields in the Manure (3220 kg ha^{-1}) and NPKS (3000 kg ha^{-1}) treatments were significantly higher than in the NKS(-P) (1640 kg ha^{-1}) and Check (1380 kg ha^{-1}) treatments. Similar trend were also observed for straw yields.

The average grain yield in the limed NPKS half-plot (3590 kg ha^{-1}) was significantly higher than in the unlimed NPKS half-plot (2400 kg ha^{-1}). The corresponding extractable P values were 19.4 and 36.9 kg P ha^{-1}. This suggests that the higher grain yield in the limed NPKS was a greater sink for extractable P. McKenzie et al. (1992) also studied the influence of lime, pH and fertilizer on the distribution of P using Hedley fractionation at the Breton Classical Plots in 1986. At the time of his sampling the pH (measured in H_2O) of the unlimed NPKS soil was 5.6 and the limed soil was 6.7, while the limed Check soil was 6.7 and unlimed was 6.4. Soil pH levels were affected by both fertilizer application, (McCoy and Webster 1977) and liming (McKenzie et al. 1992). Available P in the unlimed NPKS treatment was slightly lower than the NPKS in the limed of the same treatment (McKenzie et al. 1992), but the limed half-plots had significantly lower extractable P than the unlimed half-plots in my results. There was no significant difference in net N mineralized in the limed and unlimed half-plots of the NPKS and NKS(-P) treatments. However, the higher pH in the limed half-plots compared to the unlimed half-plots may increase the availability of nutrients such as molybdenum, boron, copper, potassium, and phosphorus and decrease the toxicity of manganese, aluminum, iron and zinc (Troeh and Thompson 1993).

There were no significant differences in the magnitudes of the MOM fraction and its C, N and P contents, but there were significant main and interaction differences with respect to the MOM C:N, N:P and C:P ratios. In this study, the C, N and P content of the grain and straw were not available, however the wide MOM C:P ratios in the treatments without P (ranging from 90-143 in the 0-7.5 cm depth) clearly show that there was a lack of available P for optimal growth. The wide MOM C:P ratios in the NKS(-P) and Check treatments are consistent with the significantly lower grain and straw yields for both the limed and unlimed half-plots.

The impact of Lime and P on SOM dynamics

Liming did not have a significant influence on the total C and N contents in the soils. The total soil C and N decreased with depth but the total P showed a reverse trend. McKenzie et al. (1992) reported that 48% and 53% of total P in the 0-15 cm depth of the limed and unlimed NPKS treatment of the 5-yr rotation, respectively, was in the form of

organic P. This means that total organic P decreases with depth and there is a large reservoir of inorganic P in the 15-45 cm depths. As more than 80% of the roots of cereal crops at Breton are found in the top 15 cm of soil (Izauuralde et al. 1993), it is not unusual to see lower amounts of total P in the 0-15 cm depths. However, the growth of forages, especially alfalfa, can lead to the transformation of inorganic P to organic P via plant uptake, and translocation of P from the lower depths (15-45 cm) to the surface depths (0-15 cm).

McKenzie et al. (1992) studied the dynamics of inorganic and organic forms of P in the NPKS and Check treatments of the 5-yr and 2-yr rotations at the Breton Classical Plots in 1986. They reported that lime application had a significant negative correlation to magnitudes of organic P fractions (bicarbonate and NaOH extracted) and inorganic available P fractions (resin P). The differences between the NPKS and the Manure treatment could be attributed to the decrease in stability of organic P fractions in the NPKS treatment. The dynamics of microbial biomass, and organic and inorganic P fractions need to be studied in order to understand the intricate dynamics of P in soil.

Conclusions

The addition of basic cations in manure helped to maintain a higher pH in the limed and unlimed manure treated plots. The pH in the unlimed NPKS and NKS(-P) was significantly lower than the unlimed Check treatment due to nitrification of ammoniacal inorganic fertilizer applications in these treatments. The extractable P in the Manure and NPKS treatments was significantly higher than the NKS(-P) and Check treatments and was correlated to grain and straw yields. The wide MOM C:P ratios in the NKS(-P) and Check treatments correlate with the significantly lower grain and straw yields for both the limed and unlimed half-plots.

Liming did not have a significant influence on the total C and N contents in the soils. The total soil C and N decreased with depth but the total P showed a reverse trend. There is a large reservoir of inorganic P in the 15-45 cm depths which could be used by deep rooted perennial crops.

Future Research

The limed half-plots of the Breton Classical Plots have received another application of lime to raise the soil pH in 2001. This will lead to significant differences in soil pH between the half-plots in two to five years. A thorough assessment of the SOM dynamics in these plots using the Hedley fractionation method could yield greater insights on the impact of liming and phosphorus on soil C sequestration.

Table 3.1 Average grain and straw yields of spring wheat from 1972- 1998 on the limed and unlimed halves of the 5-yr Rotation at the Breton Classical Plots in Breton, Alberta.

Lime	Treatment	Grain (kg ha^{-1})	Straw (kg ha^{-1})
Limed	Manure	3480a	3880b
	NPKS	3590a	3990b
	NKS(-P)	1720d	2680c
	Check	1290f	1960d
Unlimed	Manure	2950b	4500a
	NPKS	2400c	3810b
	NKS(-P)	1560e	2420c
	Check	1460e	2350c

Summary of ANOVA

Source of Variation	Df	grain	straw
Lime	1	*	NS
Treatment	3	***	***
Lime x Treatment	3	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Grain = 410, Straw = 530

Table 3.2 Total Soil C, N, P contents of the 5-yr rotation at the Breton Classical Plots

Lime	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*pH*	*Total C kg C ha^{-1}*	*Total N kg N ha^{-1}*	*Total P kg P ha^{-1}*
Limed	Manure	0- 7.5	1.2a	5.7a	22 300a	2 080a	590m
		7.5-15	1.3b	5.6a	20 300b	1 940b	670k
		15- 30	1.4c	5.6a	17 300c	1 890b	1 070e
		30- 45	1.5d	5.3c	10 700g	1 430h	1 000f
	NPKS	0- 7.5	1.3b	5.3c	18 500c	1 750d	650l
		7.5-15	1.4c	5.5b	15 900d	1 550f	620l
		15- 30	1.5d	5.5b	13 700f	1 620e	1 020e
		30- 45	1.5d	5.2c	10 100g	1 380i	980g
	NKS(-P)	0- 7.5	1.3b	5.2c	17 300c	1 650e	520n
		7.5-15	1.3b	5.2c	14 100e	1 340i	500o
		15-30	1.5d	5.4b	14 000e	1 700d	950g
		30-45	1.5d	5.2c	9 200g	1 280j	920h
	Check	0- 7.5	1.2a	5.4b	14 200e	1 360i	500o
		7.5-15	1.4c	5.3c	13 400f	1 360i	570m
		15-30	1.5d	5.3c	13 200f	1 640e	1 040e
		30-45	1.5d	5.1d	8 400h	1 250j	1 050e
Unlimed	Manure	0- 7.5	1.2a	5.3c	22 600a	2 100a	680k
		7.5-15	1.4c	5.3c	19 000b	1 820c	820i
		15- 30	1.5d	5.4b	13 400f	1 740d	1 710a
		30- 45	1.5d	5.3c	9 200g	1 380i	1 600b
	NPKS	0- 7.5	1.2a	4.4f	17 800c	1 690d	650k
		7.5-15	1.4c	4.5f	15 400d	1 520g	740j
		15- 30	1.5d	5.0d	12 800f	1 670e	1 460c
		30- 45	1.5d	4.9d	9 500g	1 460h	1 290d
	NKS(-P)	0- 7.5	1.3b	4.7e	17 400c	1 690d	540n
		7.5-15	1.3b	4.8e	13 700f	1 370i	510o
		15-30	1.5d	5.1d	13 300f	1 670e	990g
		30-45	1.5d	4.9d	9 700g	1 320i	960g
	Check	0- 7.5	1.3b	5.0d	15 200d	1 490m	510o
		7.5-15	1.4c	4.9d	12 500f	1 240j	530n
		15-30	1.5d	5.0d	11 800f	1 580f	930f
		30-45	1.5d	4.9d	8 600h	1 350i	830i

Summary of ANOVA

Source of Variation	df	D_b	pH	Total C	Total N	Total P
Lime	1	NS	***	NS	NS	***
Treatment	3	*	***	***	***	***
Lime x Treatment	3	NS	NS	NS	***	***
Depth	3	***	NS	***	NS	***
Lime x Depth	3	NS	NS	NS	NS	*
Treatment x Depth	9	NS	NS	***	***	NS
Lime x Treatment x Depth	9	NS	NS	NS	NS	*

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Bulk Density = 0.029; pH = 0.15 Total C = 980; Total N = 60; Total P = 30 *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant

Table 3.3 Total Soil C, N, P ratios at four depths of the5-yr rotation at the Breton Plots

Lime	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*C:N*	*N:P*	*C:P*	*C:*	*N:*	*P*
Limed	Manure	0- 7.5	1.2	10.7a	3.5a	37.5a	10.7	1	0.29
		7.5-15	1.3	10.6a	2.9a	30.8b	10.6	1	0.34
		15- 30	1.4	9.1c	1.8c	16.2f	9.1	1	0.56
		30- 45	1.5	7.5e	1.4d	10.6g	7.5	1	0.71
	NPKS	0- 7.5	1.3	10.6a	2.7b	28.4c	10.6	1	0.37
		7.5-15	1.4	10.2a	2.5b	25.5d	10.2	1	0.40
		15- 30	1.5	8.5c	1.6c	13.5f	8.5	1	0.63
		30- 45	1.5	7.3e	1.4d	10.3g	7.3	1	0.71
	NKS(-P)	0- 7.5	1.3	10.5a	3.2b	33.5b	10.5	1	0.31
		7.5-15	1.3	10.5a	2.7b	28.5c	10.5	1	0.37
		15-30	1.5	8.3d	1.8c	14.8f	8.3	1	0.56
		30-45	1.5	7.2e	1.4d	10.1g	7.2	1	0.71
	Check	0- 7.5	1.3	10.4a	2.7b	28.6c	10.4	1	0.37
		7.5-15	1.4	9.9b	2.4b	23.6d	9.9	1	0.42
		15-30	1.5	8.0d	1.6c	12.7g	8.0	1	0.63
		30-45	1.5	6.7f	1.2d	8.0h	6.7	1	0.83
Unlimed	Manure	0- 7.5	1.2	10.7a	3.1a	33.1b	10.7	1	0.32
		7.5-15	1.5	10.4a	2.2b	23.2e	10.4	1	0.45
		15- 30	1.4	7.7d	1.0d	7.9h	7.7	1	1.0
		30- 45	1.5	6.6f	0.86e	5.7i	6.6	1	1.2
	NPKS	0- 7.5	1.2	10.5a	2.6b	27.6c	10.5	1	0.38
		7.5-15	1.5	10.1a	2.1c	20.9e	10.1	1	0.48
		15- 30	1.5	7.7d	1.1d	8.8h	7.7	1	0.91
		30- 45	1.5	6.5f	1.1d	7.8h	6.5	1	0.91
	NKS(-P)	0- 7.5	1.4	10.3a	3.1a	32.2b	10.3	1	0.32
		7.5-15	1.5	10.0a	2.7b	26.9c	10.0	1	0.37
		15-30	1.5	8.0d	1.7c	13.4f	8.0	1	0.59
		30-45	1.5	7.3e	1.4d	10.1g	7.3	1	0.71
	Check	0- 7.5	1.3	10.3a	2.9a	29.9b	10.3	1	0.34
		7.5-15	1.4	10.1a	2.4b	23.9e	10.1	1	0.42
		15-30	1.5	7.5e	1.7c	12.7g	7.5	1	0.59
		30-45	1.5	6.4f	1.6c	10.4g	6.4	1	0.63

Summary of ANOVA

Source of Variation	df	D_b	C:N	N:P	C:P
Lime	1	NS	NS	***	***
Treatment	3	*	NS	*	*
Lime x Treatment	3	NS	NS	*	NS
Depth	3	***	***	***	***
Lime x Depth	3	NS	NS	*	*
Treatment x Depth	9	NS	NS	NS	NS
Lime x Treatment x Depth	9	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different (P<0.05); LSD: C:N = 0.7; N:P = 0.6; C:P = 3.2 *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 3.4: Total C, N, P contents in MOM of the limed and unlimed halves of the 5-yr Rotation at the Breton Classical Plots in Breton, Alberta (1998 sampling)

Lime	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*MOM kg ha^{-1}*	*MOM C kg C ha^{-1}*	*MOM N kg N ha^{-1}*	*MOM P kg P ha^{-1}*
Limed	Manure	0- 7.5	1.2	2 380b	840a	38a	7.6a
		7.5-15	1.3	1 350c	560c	28b	8.3a
	NPKS	0- 7.5	1.3	2 840b	750b	32b	6.8a
		7.5-15	1.4	800d	290d	11c	2.5c
	NKS(-P)	0- 7.5	1.3	2 510b	930a	38a	6.8a
		7.5-15	1.3	1 120c	470c	14c	2.5c
	Check	0-7.5	1.3	1 910c	810a	33b	6.5a
		7.5-15	1.4	740d	310d	11c	2.3c
Unlimed	Manure	0- 7.5	1.2	2 240b	860a	36a	5.9b
		7.5-15	1.4	990d	290d	11c	2.9c
	NPKS	0- 7.5	1.2	3 530a	890a	39a	8.6a
		7.5-15	1.4	750d	250d	8.3c	1.7d
	NKS(-P)	0- 7.5	1.3	3 160a	620b	35a	6.8a
		7.5-15	1.3	1 200c	320d	11c	2.5c
	Check	0- 7.5	1.3	1 530c	530c	18c	3.7c
		7.5-15	1.4	840d	270d	8.3c	2.0c

Summary of ANOVA

Source of variation	df	MOM	MOM C	MOM N	MOM P
Lime	1	NS	NS	NS	NS
Treatment	3	NS	NS	NS	NS
Lime x Treatment	3	NS	NS	NS	NS
Depth	3	***	***	***	***
Lime x Depth	3	NS	NS	NS	NS
Treatment x Depth	9	NS	NS	NS	NS
Lime x Treatment x Depth	9	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: MOM C = 149; MOM N = 7.05; MOM P = 1.97 *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 3.5 MOM C, N, P Ratios in MOM at two depths from limed and unlimed 5-yr rotation

Lime	*Treatment*	*Depth (cm)*	*D_b g cm^{-3}*	*MOM kg ha^{-1}*	*C:N*	*N:P*	*C: P*	*C:*	*N:*	*P*
Limed	Manure	0- 7.5	1.18	2 380a	22e	5.0b	111c	22	1	0.20
		7.5-15	1.28	1 350a	20f	3.4d	67.2e	20	1	0.30
	NPKS	0- 7.5	1.25	2 840a	24d	4.7b	111c	24	1	0.21
		7.5-15	1.36	800b	27c	4.2c	115c	27	1	0.24
	NKS(-P)	0- 7.5	1.25	2 510a	25d	5.6a	138a	25	1	0.18
		7.5-15	1.32	1 120b	33a	4.6c	151a	33	1	0.22
	Check	0- 7.5	1.25	1 910a	25d	5.1b	126b	25	1	0.20
		7.5-15	1.37	740b	29b	4.5c	132b	29	1	0.22
Unlimed	Manure	0- 7.5	1.15	2 240a	24d	6.1a	146a	21	1	0.23
		7.5-15	1.45	990b	26c	3.9d	103c	24	1	0.29
	NPKS	0- 7.5	1.20	3 530c	23e	4.5c	103e	28	1	0.25
		7.5-15	1.48	750b	30b	4.8b	143a	28	1	0.28
	NKS(-P)	0- 7.5	1.36	3 160c	18f	5.1b	90.1d	35	1	0.21
		7.5-15	1.47	1 200b	31a	4.2c	130b	29	1	0.23
	Check	0- 7.5	1.26	1 530a	29b	4.9b	143a	27	1	0.14
		7.5-15	1.41	840b	33a	4.2c	138a	33	1	0.26

Summary of ANOVA

Source of Variation	df	MOM	MOM C:N	MOM N:P	MOM C:P
Lime	1	NS	**	NS	***
Treatment	3	NS	*	*	***
Lime x Treatment	3	NS	NS	*	*
Depth	3	NS	***	***	***
Lime x Depth	3	NS	***	NS	NS
Treatment x Depth	9	NS	*	NS	NS
Lime x Treatment x Depth	9	NS	NS	NS	NS

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: MOM C:N = 1.5; MOM N:P= 0.7; MOM C:P = 14 *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 3.6 Short- Term C,N,P after a 10 week incubation experiment of the limed and unlimed halves of the 5-yr Rotation at the Breton Classical Plots in Breton, Alberta (1998 sampling)

Lime	*Treatment*	*Depth (cm)*	*Resp C [a] kg C ha^{-1}*	*Net Min N [b] kg N ha^{-1}*	*CO_2-C: N_{min}*	*Micro C [c] kg C ha^{-1}*	*RespC/ MicroC*	*Extract P [d] kg P ha^{-1}*
Limed	Manure	0- 7.5	648a	66a	9.8d	3 240e	0.20 a	23.9b
		7.5-15	445c	41c	10.8c	3 990c	0.11b	6.8e
	NPKS	0- 7.5	565b	48b	11.8b	3 990c	0.14b	19.4c
		7.5-15	324d	26e	12.3a	4 470b	0.072d	5.0f
	NKS(-P)	0- 7.5	530b	44b	12.2a	4 830a	0.11b	1.6g
		7.5-15	316d	29d	10.9c	3 920c	0.081d	1.5g
	Check	0- 7.5	518b	43c	12.1a	3 660d	0.14b	2.6f
		7.5-15	278e	22e	12.8a	2 790f	0.10c	2.0g
Unlimed	Manure	0- 7.5	571b	67a	8.5e	4 890a	0.10c	20.0c
		7.5-15	204f	35d	7.2f	2 070g	0.099c	8.7e
	NPKS	0- 7.5	527b	51b	10.3c	4 080c	0.13b	36.9a
		7.5-15	194f	28d	6.8f	1 980g	0.098c	12.0d
	NKS(-P)	0- 7.5	573b	46b	12.5a	4 200b	0.14b	1.9g
		7.5-15	349d	28d	12.6a	2 730f	0.13b	1.4g
	Check	0- 7.5	371d	41c	9.2d	3 750d	0.099c	4.2f
		7.5-15	164f	26e	6.3g	1 980g	0.083d	2.9f

Summary of ANOVA

Source of Variation	Df	Resp C	Min N	C_{min} :N_{min}	Micro C	RespC /Micro	Extract P
Lime	1	***	NS	***	*	**	***
Treatment	3	***	***	***	NS	**	***
Lime x Treatment	3	***	NS	*	NS	NS	***
Depth	3	***	***	***	*	*	***
Lime x Depth	3	NS	NS	NS	NS	NS	NS
Treatment x Depth	9	NS	NS	NS	NS	NS	***
Lime x Treatment x Depth	9	NS	NS	NS	*	NS	NS

a = Respired Cumulative CO_2- C
b = Net Mineral N
c = Microbial C after 10 week incubation
d = Extractable P

For each column, values of each variable marked with the same letter are not significantly different ($P<0.05$); LSD: Respired C = 59.10; Net Mineral N = 6.75; Carbon Respired to N Mineralized = 0.7; Microbial C = 300; Extractable P = 2.96; *, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant

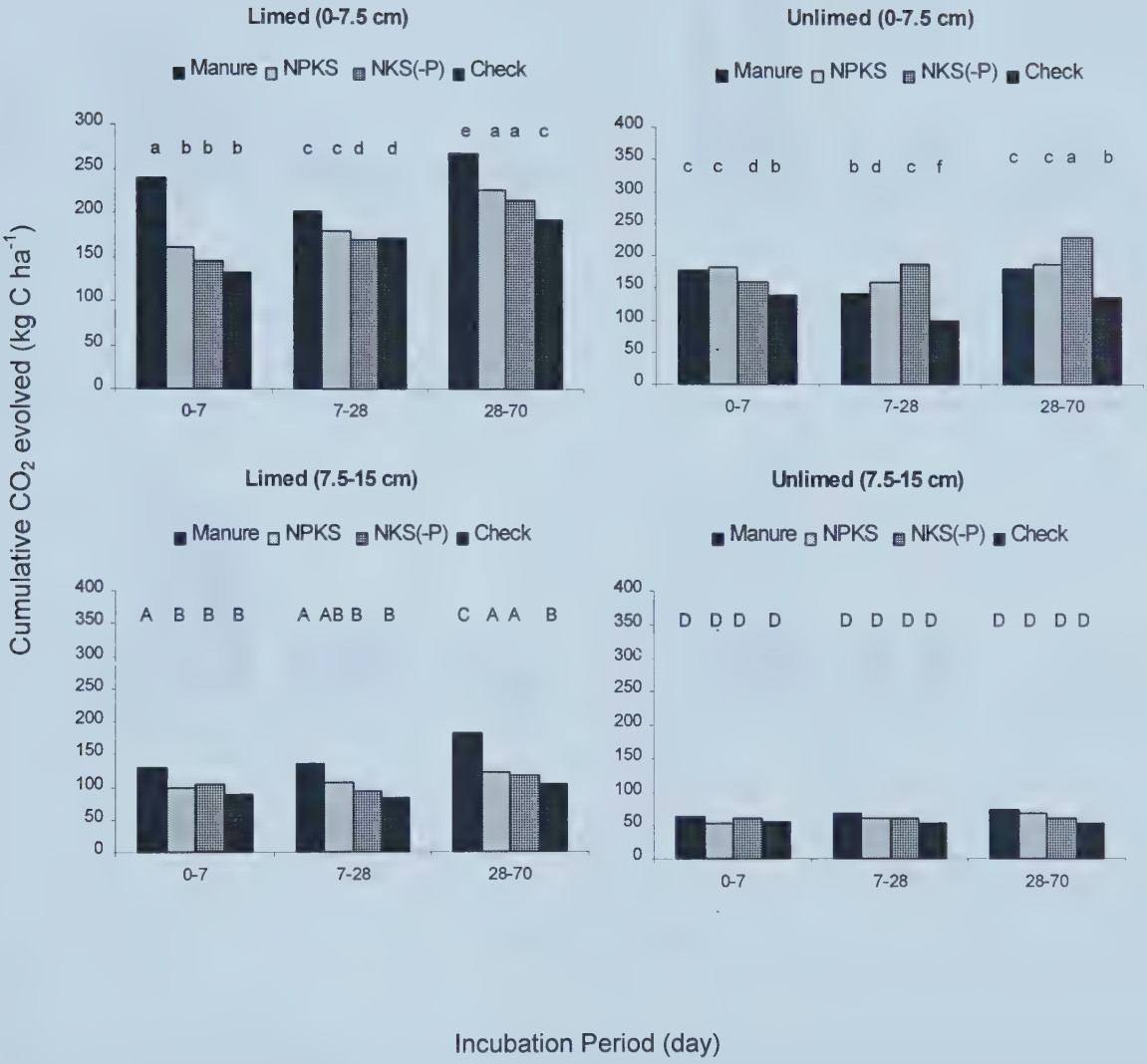

Fig. 3.1 Non- Cumulative CO_2 evolved from soil samples taken and incubated for 10 weeks at specific time intervals from the limed and unlimed halves of the 5-yr rotation at the Breton Plots. LSD: 0-7.5 cm = 41; 7.5-15 cm = 33. Bars displaying the same letter are not significantly different (P>0.05).

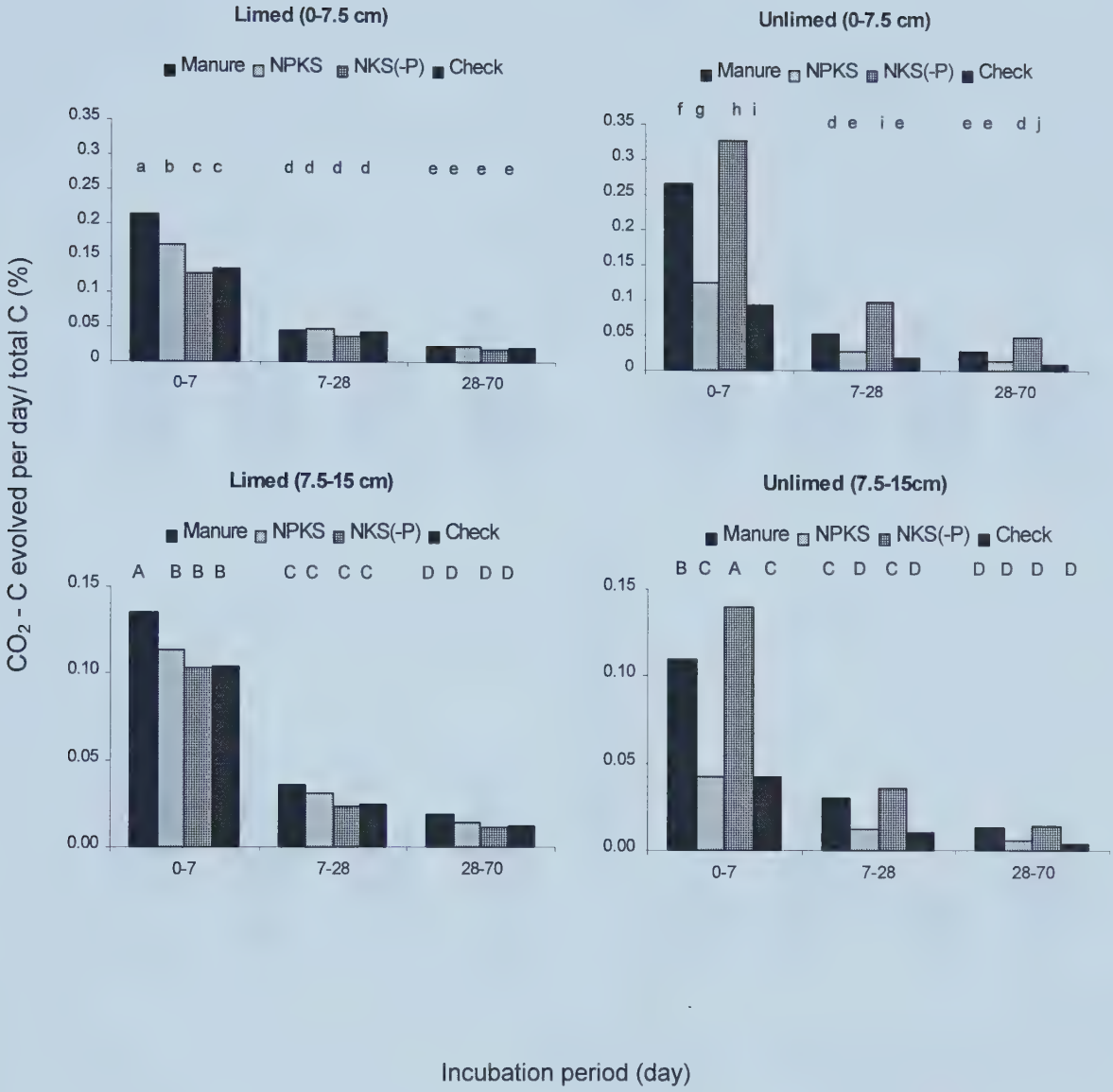

Fig. 3.2 Soil respiration expressed as a percentage of total C (CO_2-C at 3 time periods/ total C/ time x 100) for specific time periods in soil samples taken and incubated for 10 weeks at each specific time interval from the limed and unlimed halves of the 5-yr rotation at the Breton Plots; LSD: 0-7.5 cm = 0.012; 7.5-15 cm = 0.015. Bars displaying the same letter are not significantly different (P>0.05).

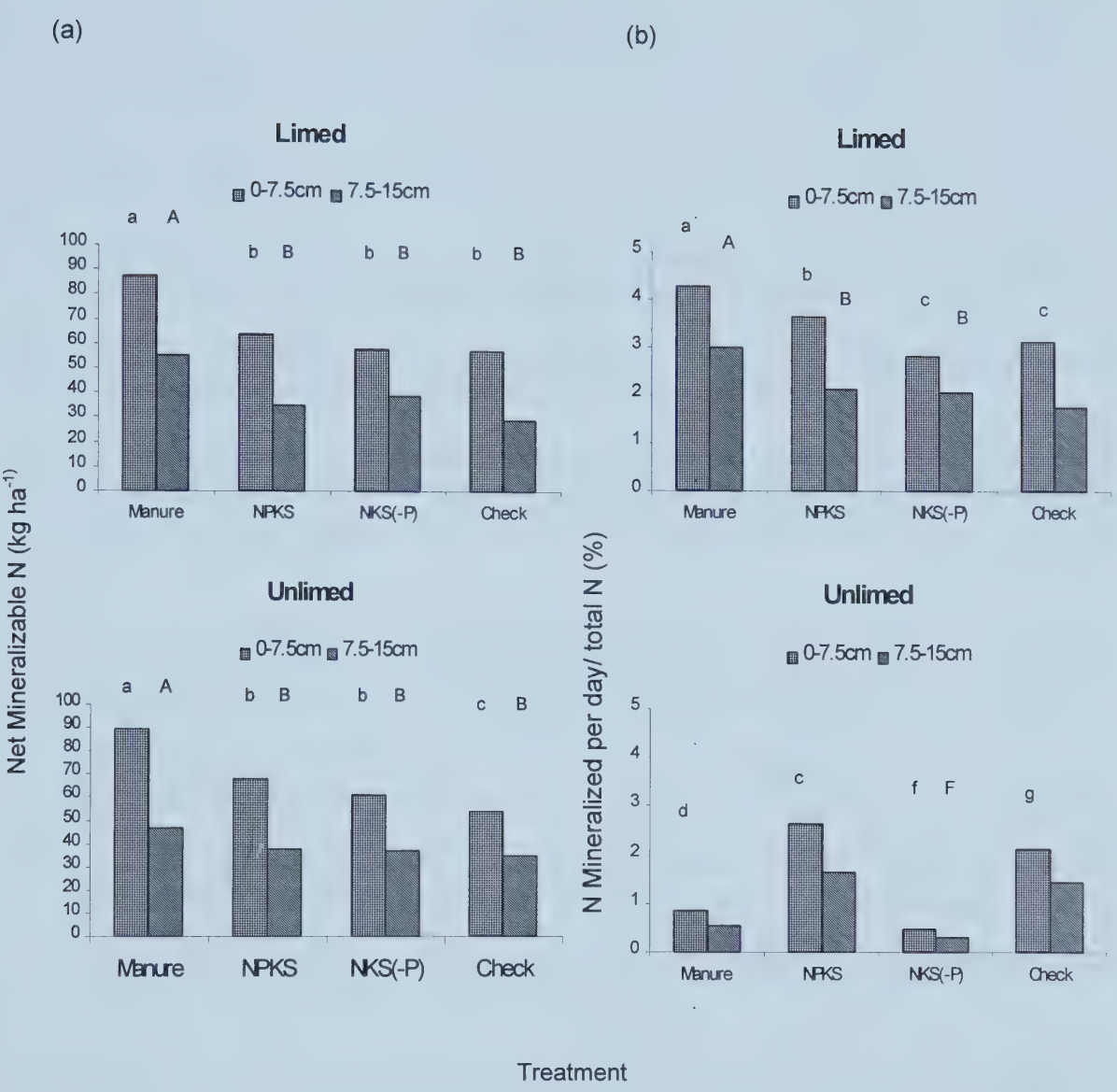

Fig. 3.3 (a) Net Mineralizable N and (b) N mineralization rate expressed as a percentage of total N (net mineralizable N/ total N x 100) for 70 days incubation weeks of soil samples taken from the limed and unlimed halves of the 5-yr rotation at the Breton Plots; LSD: Net Mineralizable N = 6.8 Total N mineralized = 0.008. Bars displaying the same letter are not significantly different (P>0.05).

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Chapter 4. Impact of P on the SOM Dynamics in ^{15}N-labeled Soils from the Breton Classical Plots under Laboratory Conditions

INTRODUCTION

Plants get all their phosphorus (P) from soil. The surface horizons of mineral soils generally contain >95% of soil C, N, and S but only 40-50% of soil P in organic forms (Tisdale et al. 1993). The dynamics of soil phosphorus are more complex than those of C, N and S because plant available phosphorus originates from several inorganic and organic sources (Hedley et al. 1982). Phosphorus levels in natural systems are essentially fixed from levels of primary apatite minerals (Bowman et al. 1998), thus C and N sequestration in soils reaches a sub-optimal steady state if P is limiting (McGill and Cole 1981).

The mineralization of P is strongly controlled by supply and need of P by microorganisms, which in turn depends upon the energy state of the soil (Hedley et al. 1982). Under net mineralization conditions, there are stoichiometric relationships between C, N and S mineralized. However, such relations are not possible between C mineralized and soluble inorganic P because the latter is in equilibrium with adsorbed and occluded forms of inorganic P. The inorganic P is readily immobilized and resolubilized by plants and microorganisms, therefore the P cycling is more complex than C, N or S cycling (McGill and Cole 1981).

The 2-yr and 5-yr crop rotations at the Breton Classical Plots are a set of long-term plots under consistent management. The amounts of fertilizer, manure and lime applied to the Breton Classical Plots for the period 1930 to 1979 were presented in Table 1.1. The treatments and nutrient application rates were revised in 1980 in which the two rotations were maintained but the nutrient application rates were changed to conform to practices for maximum yield. The design was also modified by implementing 'minus N', 'minus P', 'minus K' and 'minus S' treatments (Table 1.2) (Robertson and McGill, 1983). Lime was added to the east half of the 5-yr rotation plots (Series A-D, and F) and to the complete plots of the 2-yr rotation (Series E) in 1972 (Juma et al. 1997).

The trends of soil organic matter for the 1930 to 1979 period have been synthesized by Juma et al. (1997). Datasets have been extended to the present and have been used for further analyses (Grant et al. 2001; Izauuralde et al. 2001). These analyses have considered a large number of processes occurring in the field. In order to assess the impact of P on the dynamics of soil organic matter, it is also necessary to conduct detailed laboratory experiments.

In this chapter, a separate experiment was designed to obtain ^{15}N labeled soils from four, limed treatments (Manure, NPKS, NKS(-P) and Check) of the 2-yr and 5-yr rotation. The soil samples incubated in this experiment contained the MOM fraction. The objective of this study was to assess the impact of P on soil organic matter dynamics in ^{15}N-labeled soils from four, limed treatments of the 5-yr and 2-yr crop rotations at Breton, Alberta under laboratory conditions

MATERIALS AND METHODS

Experimental Design and Labeling Method

The limed halves of the Manure, NPKS, NKS(-P) and Check Plots of the 2-yr and 5-yr crop rotations were chosen to obtain ^{15}N labeled soil samples for laboratory incubation experiment. Metal frames (45 cm x 45 cm x 15 cm) were only installed into the plots seeded to wheat in May 1999. Wheat was grown in Series F of the 5-yr rotation and in Series E (east half) of the 2-yr rotation. Three metal frames were installed in each of the four treatments (plots 1, 2, 3, 4) of both rotations. The experimental design was 2 rotations x 4 treatments x 3 replicates (frames). In order to uniformly label the soil, a plastic mesh (11.25 cm x 11.25 cm cell size) was placed inside the frame (16 cells) and 62.5 ml of ^{15}N labeled urea solution (99.7% atom abundance applied at the rate of 2 kg N ha^{-1} soil) was injected into the soil with a syringe in the middle of each cell. One litre of de-ionized water was evenly applied to the labeled soil in each cell to allow further penetration of the labeled urea. Field sampling of ^{15}N labeled vegetation and soils was conducted in October 1999. All the above ground vegetation within the frame was cut to the soil surface. The soil within the frame was excavated to a depth of 12.5 cm, weighed and mixed on a plastic sheet. One kilogram soil sample was taken and the rest of the ^{15}N

labeled soil was returned to the frame. All soil samples were sieved with a 2 mm mesh and kept at 4°C in a cold room before analysis.

Laboratory Incubation Experiments and Analytical Methods

The ^{15}N labeled field moist fresh soil was used in the 16 week incubation experiments. Soil microbial biomass C, N and P were measured in this experiment and extractable P was measured at every sample point of the experiment. The MOM fraction was not removed from these soils as was done in the incubation experiments for Chapters 2 and 3 as I wanted to examine the dynamics of the whole soil.

This experiment involved an incubation conducted over 16 weeks to examine soil C and N mineralization, and dynamics of microbial biomass C, N, and P under standard laboratory conditions. The samples used were taken from the limed half of the Manure, NPKS, NKS(-P) and Check treatments of both the 2 yr and 5 yr rotations at the Breton Classical Plots (2 rotations x 4 treatments x 3 replicates = 24 samples). The one kilogram soil samples from each frame were subdivided into seven portions which were destructively sampled at 0, 2, 4, 6, 8, 12 and 16 weeks.

For each set, the field moist soil samples (equivalent mass of 70 g soil on an oven dry basis) were measured into polyethylene specimen cups and the moisture content was adjusted to 80% field capacity after determining the gravimetric water content of the samples. The protocol for gravimetric water content and 80% field capacity was described in chapter 2.

The soil samples were placed in a 2L Mason jars. Two vials containing 25 mL of 0.25M NaOH to trap CO_2 evolution from the soil and 10 mL deionized water to maintain humidity were also placed in the jars. All jars were sealed and incubated in the dark at 22°C. Every four weeks the samples were aerated and moistened up to 80% field capacity, if necessary.

For each sampling day the CO_2 traps were removed and titrated with 0.25M standardized HCl. Exactly 20 g moist soil was weighed from each sample and extracted with 80 mL of 2M KCl for 1 hour for mineral N analysis. The NO_3^--N in these samples

were analyzed for ^{15}N abundance. Two more portions of 20 g were used to measure microbial C and N. One portion was fumigated with ethanol-free CH_3Cl for 24 h while the other was left unfumigated. Both fumigated and unfumigated soils were incubated again for 10 days at 22°C in 2L Mason jars with a 25 mL 0.25 M NaOH trap. At the end of 10 days, the traps were titrated with standardized 0.25M HCl and the fumigated and unfumigated soil samples were extracted with 80 ml 2M KCl for 1 hour. The extracts were analyzed for mineral N content. The NH_4^+-N in the 10 day fumigated-incubated soil samples were analyzed for ^{15}N abundance to represent the ^{15}N abundance of biomass N. The soil extracts were diffused onto disks for analysis of the mineralized ^{15}N and biomass ^{15}N using the diffusion protocol described by Brooks et al. (1989). The ^{15}N in diffusion disks was subsequently analyzed on mass spectrometer, SIRA (Stable Isotope Ratio Analyser) model 10.

Absolute amounts of respired C and soil microbial biomass C was calculated based on the amount of CO_2 evolved from point zero to the sampling date (Anderson 1982) (Appendix A) and during the 10 day chloroform fumigation- incubation method (Jenkinson and Powlson 1976):

For microbial C, a K_C factor of 0.41 was used (Anderson and Domsch 1978). For microbial N, calculations were based on the difference between fumigated and unfumigated mineral N. The average K_N factor used was 0.21 based on the following equation: $K_N = -0.014\ (Cf/Nf) + 0.39$, where Cf is the amount of CO_2-C evolved from the fumigated sample and Nf is the amount of NH_4^+ extracted from the fumigated sample (Voroney and Paul 1984).

Extractable P was measured at each sampling date using the modified Miller-Axley extraction method (5 g soil to 25 ml 0.03 M NH_4-F + 0.03 M H_2SO_4) in which soils were extracted for 10 minutes (Mahli et al. 1991) and filtrates were analyzed on the Technicon 4000 Autoanalyser.

Microbial P was measured only on week 0 and week 16 using the protocol of Brookes et al. (1982). In summary, the method used 3 portions of 5 g of oven dry equivalent moist soil. The first 5 g portion was fumigated with ethanol free chloroform for 24 hours

at 22°C while the other two were incubated aerobically without fumigation for the same period of time. Subsequently, the fumigated and one of the unfumigated samples were extracted with 100 mL of 0.5 M $NaHCO_3$. The other unfumigated sample was extracted with a solution of 0.5 M $NaHCO_3$ "spiked" with 25 μg P g^{-1} as KH_2PO_4. This "spiked" $NaHCO_3$ solution acted as a correction factor for P adsorbed by soil particles. Measurement of phosphate in the extracts was measured colorimetrically at 712 nm wavelength with a spectrophotometer using the protocol of Brookes et al. (1982).

Statistical calculations were made using Statistical Analysis Systems (SAS) by the general linear model method (two factor analysis of variance) and mixed model analysis. The mixed model design was used to compare the C, N, and ^{15}N mineralization with the repeated measurement statement in SAS (SAS Institute Inc. 1990). All reported results are the means of all replicates within a specific treatment. Duncan's Multiple Range test and the Boneferroni t- tests were used to test differences in means.

RESULTS

Total C, N and P content

The soil total C and N concentrations in 0-12.5 cm depth were significantly different between the two rotations and among the four treatments but for soil P there was only a significant difference between the treatments (Table 4.1). In both rotations, there was no significant difference in total C content between NPKS and NKS(-P) (26.1 and 25.3 g kg^{-1} soil) for the 5-yr rotation and (13.9 and 12.5 g kg^{-1} soil) for the 2-yr rotation. The Manure treatment had significantly higher amount of total C in both rotations (35.4 and 30.9 g kg^{-1} soil). The average total N of the 5-yr rotation (2.60 g kg^{-1} soil) was approximately 1.5 times higher than that of the 2-yr rotation (1.80 g kg^{-1} soil). The average total N for the Manure, NPKS, NKS(-P) and Check were 3.1 , 2.0 , 2.0 , and 1.7 g kg^{-1} soil, respectively. The Manure treatment total N was about 1.8 times higher than the Check treatment.

The total P followed a different trend with respect to treatment when compared total C and N and there were no significant differences attributed to rotation (Table 4.1). The NKS(-P) and Check treatments were significantly lower than the Manure and NPKS

treatments. The average total P for Manure, NPKS, NKS(-P), and Check treatments in the 0-12.5 cm depth were 1.0, 0.73, 0.54, and 0.53 g kg^{-1} soil, respectively.

Microbial biomass C, N, ^{15}N, and P dynamics

There were no significant differences in the amount of microbial biomass C over the 16-wk period for all soil samples within each treatment (Fig. 4.1, Table 4.4). However, there was a significant difference in the amount of microbial C between the two rotations and among the four treatments. The microbial C in the 5-yr rotation (850 mg kg^{-1} soil) was higher than that in the 2-yr rotation (530 mg kg^{-1} soil). The average microbial C in the Manure treatment was approximately 900 mg kg^{-1} soil compared to 760 mg kg^{-1} soil for the NPKS treatment. The microbial C in NKS(-P) and Check (670 and 590 mg kg^{-1} soil, respectively) was significantly lower than that of the Manure and NPKS treatments (Fig. 4.1).

Microbial N showed significant differences in the averages between the two rotations and among four treatments. Microbial N in the 5-yr rotation (120 mg kg^{-1} soil) was significantly higher than that in the 2-yr rotation (100 mg kg^{-1} soil) (Table 4.4, Fig. 4.2). Microbial N in the Manure (142 mg kg^{-1} soil) and NPKS (115 mg kg^{-1} soil) treatments was significantly higher than that in the NKS(-P) (93 mg kg^{-1} soil) and Check (88 mg kg^{-1} soil) treatments. Over the 16 week incubation soil microbial N decreased over time (Fig. 4.2). The decrease in microbial N for soils from the 5-yr rotation in the Manure, NPKS, NKS(-P) and Check treatments was -1.03, -0.89, -0.71 and -0.45 mg kg^{-1} soil day^{-1}, respectively. The magnitude of biomass N in the NKS(-P) treatment was significantly lower than that of the treatments with P. There was no significant difference in the rate of microbial N decrease among the NKS(-P) and Check treatments. The decrease in activity of microbial N of the 2-yr rotation ranged from -0.45 to -0.35 mg kg^{-1} soil day^{-1}. The microbial N decreased at a faster rate in the NKS(-P) and Check than in the Manure and NPKS treatments. There was no significant difference in the magnitude of microbial N between Manure and NPKS treatments, and the NKS(-P) and Check treatments over time.

The average microbial ^{15}N across all sampling points and replicates was significantly higher in the 5-yr rotation (111 ng g^{-1} soil) than the 2-yr rotation (78 ng g^{-1} soil). Microbial ^{15}N in the Manure (144 ng g^{-1} soil) and the NPKS (100 ng g^{-1} soil) treatments was significantly higher than that in the NKS(-P) (67 ng g^{-1} soil) and Check (69 ng g^{-1} soil) (Table 4.4). Microbial biomass ^{15}N decreased in all soils from the beginning to the end of the 16 week incubation experiment (Fig. 4.3). The data for microbial biomass ^{15}N were fitted using a first order equation ($dA/dt = kA$). All values were expressed on relative basis. The first order microbial ^{15}N rate constants for soils from the NKS(-P) and Check treatments of the 2-yr rotation were steeper (-0.71% ^{15}N remaining day^{-1}) than those for the Manure and NPKS (-0.54% ^{15}N remaining day^{-1}) of the 2-yr rotation and those in the 5-yr rotation (-0.63% ^{15}N remaining day^{-1}). The microbial ^{15}N gradients of soils from the 5-yr rotation for the all treatments were not statistically different except for the Check treatment. There was no significant difference in the microbial ^{15}N gradients between NKS(-P) and Check treatments of the 2-yr rotation.

Microbial P measured at the beginning and the end of the 16-week incubation experiment showed a significant difference in rotation and treatments but not between the two time measurements (Table 4.2). The average microbial biomass P for the 5-yr rotation (50 mg kg^{-1} at week 0 and 47 mg kg^{-1} at week 16 was significantly higher than the 2-yr rotation (30 mg kg^{-1} at week 0 and 38 mg kg^{-1} at week16). The microbial biomass P values were not significantly different among treatments except for the Check treatment, which was significantly lower than the other treatments (29 and 26 mg kg^{-1} soil for week 0 and week 16, respectively). The NKS(-P) in week 16 (35 mg kg^{-1}) was significantly lower than the Manure and NPKS treatments.

Carbon and nitrogen mineralization

The average amount of mineralized C in the 5-yr rotation (1080 mg CO_2-C kg^{-1} soil) was significantly higher than that in the 2-yr rotation (473 mg CO_2-C kg^{-1} soil) (Table 4.4, Figure 4.4a). In the 5-yr rotation, the Manure (1160 mg CO_2-C kg^{-1} soil) and NPKS (850 mg CO_2-C kg^{-1} soil) treatments had significantly higher CO_2-C evolution than the NKS(-P) (700 mg CO_2-C kg^{-1} soil) and Check (390 mg CO_2-C kg^{-1} soil) treatments. (Table 4.3).

There was a significant difference in the N mineralization between the two rotations during the 16-wk incubation (Table 4.3). The average cumulative mineralized N in the 5-yr rotation (130 mg kg^{-1} soil) was more than two-fold higher than the 2-yr rotation (62 mg kg^{-1} soil) (Table 4.3). In both rotations, the cumulative N mineralized was in the order Manure (124 mg N kg^{-1} soil)> NPKS (103 mg N kg^{-1} soil)> NKS(-P) (79 mg N kg^{-1} soil) = Check (77 mg N kg^{-1} soil) (Table 4.3).

The ratio of C to N mineralized during the incubation experiment did not differ significantly between the two rotations but there were significant differences between treatments (Table 4.3). The highest C to N mineralization ratio occurred in the Manure treatments of both rotations (9.4) and in the NKS(-P) treatment of the 5-yr rotation. The lowest ratio was from the Check treatments (5.2 for the 5-yr rotation and 5.0 for the 2-yr rotation).

The amount of mineralized ^{15}N over the 16 weeks was significantly higher in the 5-yr rotation (44 ng g^{-1}) than the 2-yr rotation (37 ng g^{-1}) (Table 4.4). The NKS(-P) (31 ng g^{-1}) and Check (29 ng g^{-1}) treatments were significantly lower than the Manure (56 ng g^{-1}) and NPKS (46 ng g^{-1}) treatments. Over the course of the 16 week incubation, the mineral ^{15}N increased as the microbial ^{15}N decreased (Fig. 4.6 and 4.3).

Extractable P

Soil extractable P did not change significantly over the 16-wk incubation (Fig. 4.7). The 2-yr rotation (33 mg kg^{-1}) had a significantly higher amount of extractable P than that of the 5-yr rotation (13 mg kg^{-1}). In the 5-yr rotation, the Manure (25 mg P kg^{-1}) and NPKS (23 mg kg^{-1}) treatments were similar and the NKS(-P) (2 mg P kg^{-1}) and Check (3 mg kg^{-1}) treatments were similar (Fig. 4.7). In the 5-yr rotation, the extractable P values from treatments with P additions were about 7 times higher than those in treatments without P. In the 2-yr rotation, the trends for extractable P were Manure > NPKS > NKS(-P) ≥ Check. The Manure treatment in the 2-yr rotation was significantly higher than any of the other treatments (85 mg kg^{-1}) and the NPKS treatment was significantly lower than the Manure treatment (32 mg kg^{-1}). The two treatments with P were significantly higher than the NKS(-P) and Check treatments (5 and 8 mg kg^{-1},

respectively). In the 2-yr rotation, the extractable P values from of the NPKS and Manure treatments were about 4 and 10 times higher than those in treatments without P.

Indicators of microbial activity

The specific soil respiration rate during the 16-wk incubation was calculated as CO_2-C respired per day as a percentage of total soil C (Fig. 4.4b). Specific soil respiration rate decreased over the duration of the incubation. In the 5-yr rotation, there was no significant difference between NPKS, Manure and NKS(-P) treatments in specific soil respiration rates but the Check treatment had significantly lower values. There was no significant difference in specific respiration rates between the Manure and NKS(-P) treatments. In the 2-yr rotation, the NKS(-P) slope and magnitude was significantly different than the other treatments and was the second lowest compared to the other treatments.

The specific soil respiration activity (qCO_2) was calculated as the CO_2 production per unit biomass and per unit time (Fig. 4.8). It is an index of metabolic activity of the soil microbial biomass. The trend of qCO_2 was different from that of the specific respiration rate for treatments in the 2-yr rotation only but showed similar trends between rotations (Fig. 4.4). In the 5-yr rotation, there were significant differences in the Check in contrast to all other treatments. In the 2-yr rotation, there was no significant difference in qCO_2 among any or all treatments.

The specific soil N mineralization rate during the 16-wk incubation was calculated as mineralized N per day as a percentage of total soil N (Fig 4.5b). Specific soil N mineralization rate decreased greatly and leveled off after week 8 in all soils from both rotations and all treatments. In the 5-yr rotation, there was no significant difference in the specific N mineralization rate among treatments, except for the Manure treatment, which showed a significantly steeper. In the 2-yr rotation, the treatments with P were significantly higher than those without P and there was no significant difference between the NKS(-P) and Check treatments (Fig 4.5).

The relationship of soil microbial biomass to the total soil C and N is shown in Table 4.4. Soil microbial biomass C and total C all decreased from Manure to the Check

treatments in both rotations. The 5-yr rotation had a relatively higher mineralized CO_2-C than the 2-yr rotation (Table 4.4). The amount of mineralized CO_2-C was highest in the Manure treatment of both rotations. On average, microbial C accounted for 3.3 % of total C in the 5-yr rotation and 3.2 % of total C in the 2-yr rotation. The NPKS treatment of the 2-yr rotation had the highest percentage of microbial C to total C (4.6 %). Comparing the percentage of CO_2-C evolved per day to total C, the ratios for all treatments were significantly lower for Check treatments in both rotations (0.25% for the 5-yr and 0.18% for the 2-yr). The same trend held for the ratio of CO_2-C to microbial biomass C (0.66% and 0.58% per day in the Check treatments of the 5-yr and 2-yr rotations) (Table 4.4).

Soil microbial N, soil total N and N mineralized in 16-wk from soils decreased from Manure to Check treatments (Table 4.4). The 2-yr NPKS treatment (7.2) had the highest percentage of microbial N to total N. The N mineralization ratio (N mineralized day^{-1}/total N) followed a different trend to those of the C mineralization during the 16-wk incubation. The percentages of mineralized N to total N were the highest in the 5-yr NPKS (0.50%) and the 5-yr Check (0.45%). The same was applicable for the ratio of mineralized N to biomass N. The 5-yr NPKS and Check had the highest values.

Soil ^{15}N mineralized had a similar trend to the C and N mineralization. The soils of the Manure and NPKS treatments had higher microbial biomass ^{15}N and total ^{15}N (Table 4.4). The lowest amount of mineralized ^{15}N occurred in the NKS(-P) and Check treatments in both rotations (Table 4.4). The ratio of microbial biomass ^{15}N to total ^{15}N was highest in the Manure (1.9%) and NPKS (1.7%) treatments from the 5-yr and in the 2-yr rotation (Manure = 2.6% and NPKS = 2.7%). The ratio of mineralized ^{15}N to total ^{15}N was significantly lower in the NKS(-P) and Check treatments in contrast to those in the Manure and NPKS treatments in both rotations (Table 4.4). The ratio of mineralized ^{15}N to biomass ^{15}N was highest in the 2-yr NPKS, NKS(-P), and Check treatments.

DISCUSSION

Availability of P in different treatments of the two rotations

The soil total C and N concentrations in 0-12.5 cm depth were significantly different between the two rotations and among the four treatments but for soil P there was only a significant difference between the treatments (Table 4.1). In both rotations, there was no significant difference in total C and N content between NPKS and NKS(-P). The Manure treatment had significantly higher amount of total C in both rotations. The total P followed a different trend with respect to treatment when compared total C and N and there were no significant differences attributed to rotation (Table 4.1). The NKS(-P) and Check treatments were significantly lower in total P than the Manure and NPKS treatments. The amount of total C, N, and P in soil samples from 0-12.5 cm depth from both the 5-yr and 2-yr rotations showed similar trends to the soil samples in the 0-7.5 and 7.5-15 cm depths taken in 1998 (Table 2.2).

The slopes of soil extractable P were not significantly different from zero but the intercepts were significantly different over the 16-wk incubation (Fig. 4.7). In the 5-yr rotation, the extractable P values from treatments with P additions were about 7 times higher than those in treatments without P. In the 2-yr rotation, the extractable P values from of the NPKS and Manure treatments were about 4 and 10 times higher than those in treatments without P. These results are consistent with those reported in Chapter 2 (Table 2.6). The amounts of extractable P in treatments with P have more than adequate amounts required for microbial growth.

Impact of P on kinetics of C and N pools

The slopes of microbial C were not significantly different from zero but the intercepts were significantly different in the treatments over the 16-wk incubation (Fig. 4.1). The microbial C was greater in the 5-yr rotation compared to the 2-yr rotation and the trend among treatments was Manure > NPKS > NKS(-P) > Check (Table 4.4). The CO_2-C evolved in different treatments followed a curvilinear trend (Fig 4.4) and the amount of CO_2-C evolved in different treatments of the two rotations were consistent with the size of microbial C, with the exception of the 5-yr NKS(-P) treatment (Table 4.3). The daily

C respiration rate also followed the same trend with the exception of NKS(-P) treatment of the 5-yr rotation (Table 4.3).

The slopes of microbial N were significantly different from zero over the 16-wk incubation (Fig. 4.2). The microbial N was greater in the 5-yr rotation compared to the 2-yr rotation. In the 2-yr rotation, the average microbial N values among treatments with P were greater than the treatments without P. In the 5-yr rotation the average microbial N values were: Manure > NPKS = NKS(-P) > Check (Fig. 4.2, Table 4.4). The N mineralized values were greater in the 5-yr rotation compared to the 2-yr rotation. In both rotations the average N mineralized values were: Manure > NPKS > NKS(-P) = Check (Fig 4.5a, Table 4.3). The daily N mineralization rates in treatments with P were significantly higher than those without P (Table 4.3). These data suggest that phosphorus significantly influences the amount of N being mineralized (Table 4.3).

The percent microbial ^{15}N remaining in soil decreased exponentially (Fig. 4.3). In the 2-yr rotation microbial ^{15}N decreased at a steeper rate in treatments without P, but there was no significant difference between treatments in the 5-yr rotation. The average microbial ^{15}N was significantly lower in treatments without P compared to those with P (Table 4.4) The amount of ^{15}N mineralized was also significantly lower in treatments without P. The ratio of daily ^{15}N mineralization rate: total ^{15}N was also significantly lower in the treatments without P. These data show that the turnover rates of ^{15}N are lower in the treatments without P. These tracer data show that P controls N mineralization.

Conclusions

This laboratory incubation study has revealed that carbon mineralization is controlled by the microbial activity and initial amount of soil organic C. The ratio of C_{min}:N_{min} was between 5.0-9.4 in this experiment, therefore the soil was in net N mineralization conditions. The amount of net N mineralized was significantly lower in the treatments without P compared to those with P. The ratio of daily ^{15}N mineralization rate: total ^{15}N was significantly lower in treatments without P. These data show that the

turnover rates of ^{15}N were controlled by the availability of P. This study showed that availability of P controls N mineralization under laboratory conditions.

Future Research

The results of this study have to tested on other soils and crop rotations under field conditions. The impact of P on N mineralization has to be related to crop growth and C sequestration is soil.

Table 4.1 Soil total C, N, and P contents in 0-12.5 cm depth in soils from the 5-yr and 2-yr rotations and four treatments collected within the metal frames.

	Total C (g kg^{-1})	Total N (g kg^{-1})	Total P (g kg^{-1})
	5-yr Rotation (WOBHH)		
Manure	35.4a	3.34a	0.984a
NPKS	26.1b	2.53b	0.744b
NKS(-P)	25.3b	2.50b	0.561c
Check	19.5c	2.08c	0.553c
	2-yr Rotation (WF)		
Manure	30.9a	2.85b	1.06a
NPKS	13.9d	1.49d	0.707b
NKS(-P)	12.5d	1.51d	0.525c
Check	12.1d	1.29e	0.512c
	Summary of ANOVA		
Source of variation	Total C	Total N	Total P
Rotation	***	***	NS
Treatment	***	***	***
Rotation × Treatment	NS	NS	NS

For each column, values marked with the same letter are not significantly different ($P<0.05$)
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 4.2. Initial and final soil microbial biomass P in 0-12.5 cm depth in soils from the 5-yr and 2-yr rotations with four treatments at the Breton Plots after 16-wks incubation.

	Microbial biomass P (mg kg^{-1})	
	Initial (week 0)	Final (week 16)
	5-yr Rotation (WOBHH)	
Manure	58 a	63 a
NPKS	57 a	53 a
NKS(-P)	52 a	43 b
Check	32 b	30 c
	2-yr Rotation (WF)	
Manure	31 b	55 a
NPKS	32 b	48 a
NKS(-P)	29 b	26 c
Check	26 c	22 d

Summary of ANOVA	
Source of variation	Microbial biomass P
Time	NS
Rotation	***
Time × Rotation	NS
Treatment	**
Time × Treatment	NS
Rotation x Treatment	NS

For each row and column, values of each variable marked with the same letter are not significantly different ($P<0.05$); Letters are comparisons among time, rotation and treatments.
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

Table 4.3 Sums of mineralized C and N, ratios of mineralized C and N, and zero-order C and N mineralization rate constants in soil samples in 0-12.5 cm depth from the 5-yr and 2-yr rotations in the Breton Plots over a 16-wk incubation.

Treatment	ΣCO_2-C mg kg^{-1}	ΣN_{min} mg kg^{-1}	C_{min} / N_{min}	C min rate[a] mg kg^{-1} soil day^{-1}	N min rate mg kg^{-1} soil day^{-1}
		5yr rotation (WOBHH)			
Manure	1500 a	160 a	9.4 a	13.4 a	1.4 a
NPKS	1210 b	142 b	8.5 b	10.8 b	1.3 a
NKS(-P)	1060 c	112 c	9.4 a	9.5 b	1.0 b
Check	537 e	104 c	5.2 c	4.8 d	0.9 b
		2yr rotation (WF)			
Manure	825 d	88 d	9.4 a	7.4 c	0.8 c
NPKS	484 e	63 e	7.7 d	4.3 d	0.6 c
NKS(-P)	336 f	46 f	7.3 d	3.0 e	0.4 d
Check	247 g	49 f	5.0 c	2.2 f	0.4 d
		Summary of ANOVA			
Source of Variation	ΣCO_2-C	ΣN_{min}	C_{min} / N_{min}	C min rate	N min rate
Rotation	***	***	NS	***	***
Treatment	***	***	**	**	***
Time	***	***	NS	-	-
Rot[b] x Treat[c]	NS	NS	NS	NS	NS
Treat x Time	**	NS	NS	-	-

For each column, values marked with the same letter are not significantly different ($P<0.05$)
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant.

a = mineralization rate
a = rotation
b = treatment

Table 4.4 Soil microbial biomass, total, and mineralized C and N relationships among 5-yr and 2-yr rotations at the Breton Plots by the end of 16 weeks incubation.

Treatment	Microbial C (mg kg^{-1})	Total C (g kg^{-1})	CO_2-C (mg kg^{-1})	Microbial C/Total C (%)	CO_2-C day^{-1}/ Total C (%)	CO_2-C day^{-1}/ Biomass C (%)
			5yr Rotation (WOBHH)			
Manure	981 a	35.4	1500	2.8 d	0.38 a	1.4 a
NPKS	878 b	26.1	1210	3.4 b	0.41 a	1.2 a
NKS(-P)	808 b	25.3	1060	3.2 c	0.37 a	1.2 b
Check	725 c	19.5	537	3.7 b	0.25 c	0.66 d
			2yr Rotation (WF)			
Manure	789 c	30.9	825	2.6 d	0.24 c	0.93 c
NPKS	632 d	13.9	484	4.6 a	0.31 b	0.68 d
NKS(-P)	321 e	12.5	336	2.6 d	0.24 c	0.93 c
Check	380 e	12.1	247	3.1 c	0.18 d	0.58 e
	Microbial N (mg kg^{-1})	Total N (g kg^{-1})	Mineralized N (mg kg^{-1})	Microbial N/ Total N (%)	Mineralized N day^{-1}/ Total N (%)	Mineralized N day^{-1}/ Microbial N (%)
			5yr Rotation (WOBHH)			
Manure	163 a	3.34	160	4.9 d	0.43 b	0.88 b
NPKS	122 b	2.53	142	4.8 d	0.50 a	1.04 a
NKS(-P)	104 b	2.50	112	4.2 e	0.40 b	0.96 a
Check	89 c	2.08	104	4.3 e	0.45 b	1.04 a
			2yr Rotation (WF)			
Manure	120 b	2.85	88	4.2 e	0.28 d	0.66 c
NPKS	107 b	1.49	63	7.2 a	0.38 c	0.52 d
NKS(-P)	82 c	1.51	46	5.4 c	0.27 d	0.50 d
Check	86 c	1.29	49	6.6 b	0.34 c	0.51 d
	Microbial ^{15}N (ng g^{-1})	Total ^{15}N (µg g^{-1})	Mineralized ^{15}N (ng g^{-1})	Microbial ^{15}N / Total ^{15}N (%)	Mineralized ^{15}N day^{-1}/ Total ^{15}N (%)	Mineralized ^{15}N day^{-1}/ Microbial ^{15}N (%)
			5yr Rotation (WOBHH)			
Manure	162 a	8.71 a	57 a	1.9 b	0.0058 c	35 c
NPKS	126 b	7.51 b	54 a	1.7 c	0.0064 c	43 b
NKS(-P)	79 c	6.76 c	34 b	1.2 d	0.0045 d	43 b
Check	79 c	6.14 d	31 b	1.3 d	0.0045 d	39 c
			2yr Rotation (WF)			
Manure	125 b	4.81 e	55 a	2.6 a	0.0100 a	44 b
NPKS	73 c	2.75 f	37 b	2.7 a	0.0120 a	51 a
NKS(-P)	54 d	2.52 f	27 c	2.1 b	0.0096 b	50 a
Check	59 d	2.50 g	27 c	2.4 b	0.0096 b	46 b

Summary of ANOVA

Source of Variation	Microbial ^{15}N	Total ^{15}N	Mineralized ^{15}N
Rotation	***	***	*
Treatment	*	***	**
Time	***	-	NS
Rot[A] x Treat[B]	NS	NS	NS
Treat x Time	NS	NS	NS

For each column, values marked with the same letter are not significantly different ($P<0.05$)
*, **, *** $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively; NS, not significant. A = Rotation, B = Treatment

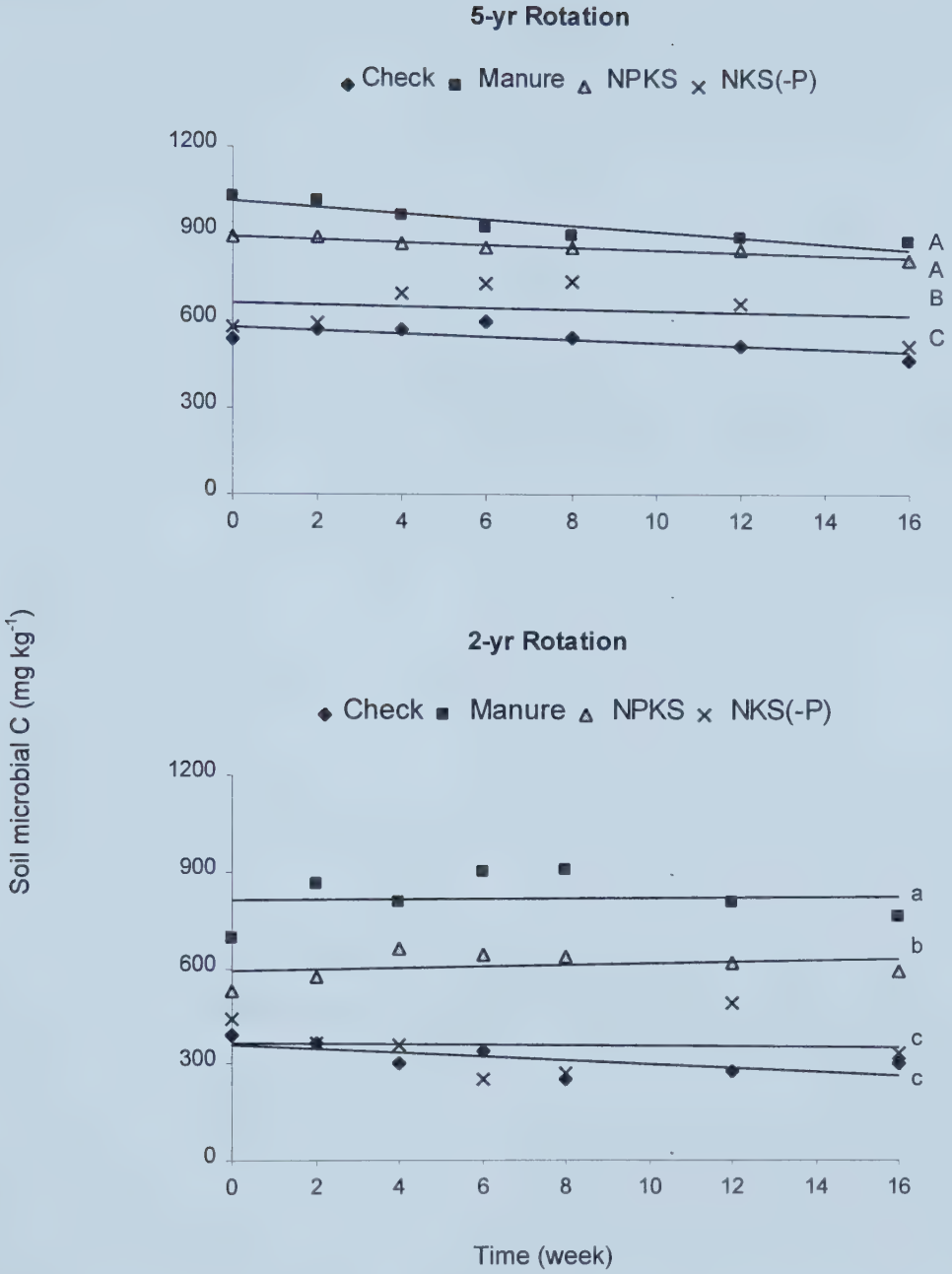

Fig 4.1. Soil microbial C from the 2-yr and 5-yr rotations with four different treatments at the Breton Plots after 16 weeks incubation; LSD = 95. Intercepts of lines carrying the same letter are not significantly different (P>0.05).

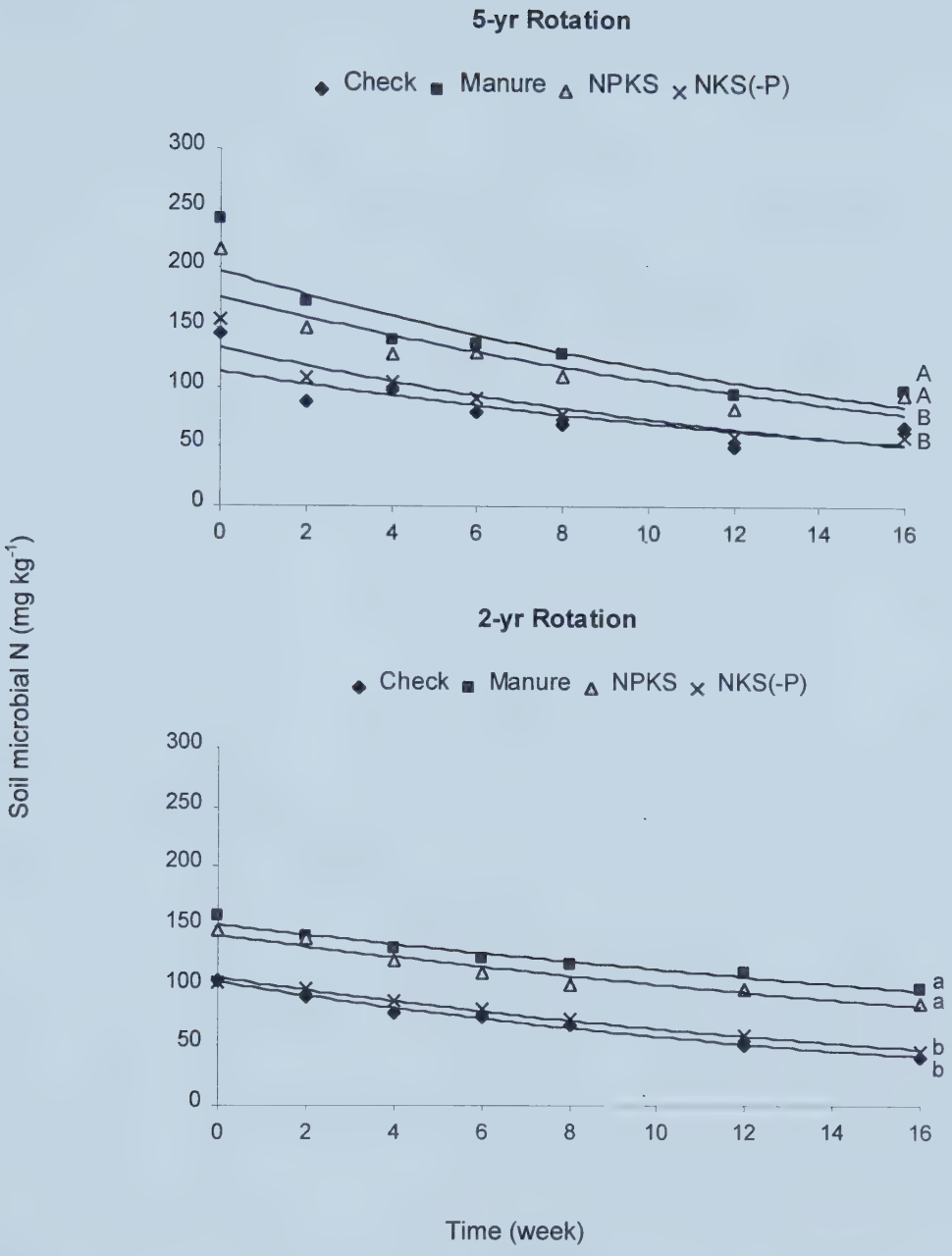

Fig 4.2. Soil microbial N from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD = 23. Slopes of lines carrying the same letter are not significantly different (P>0.05).

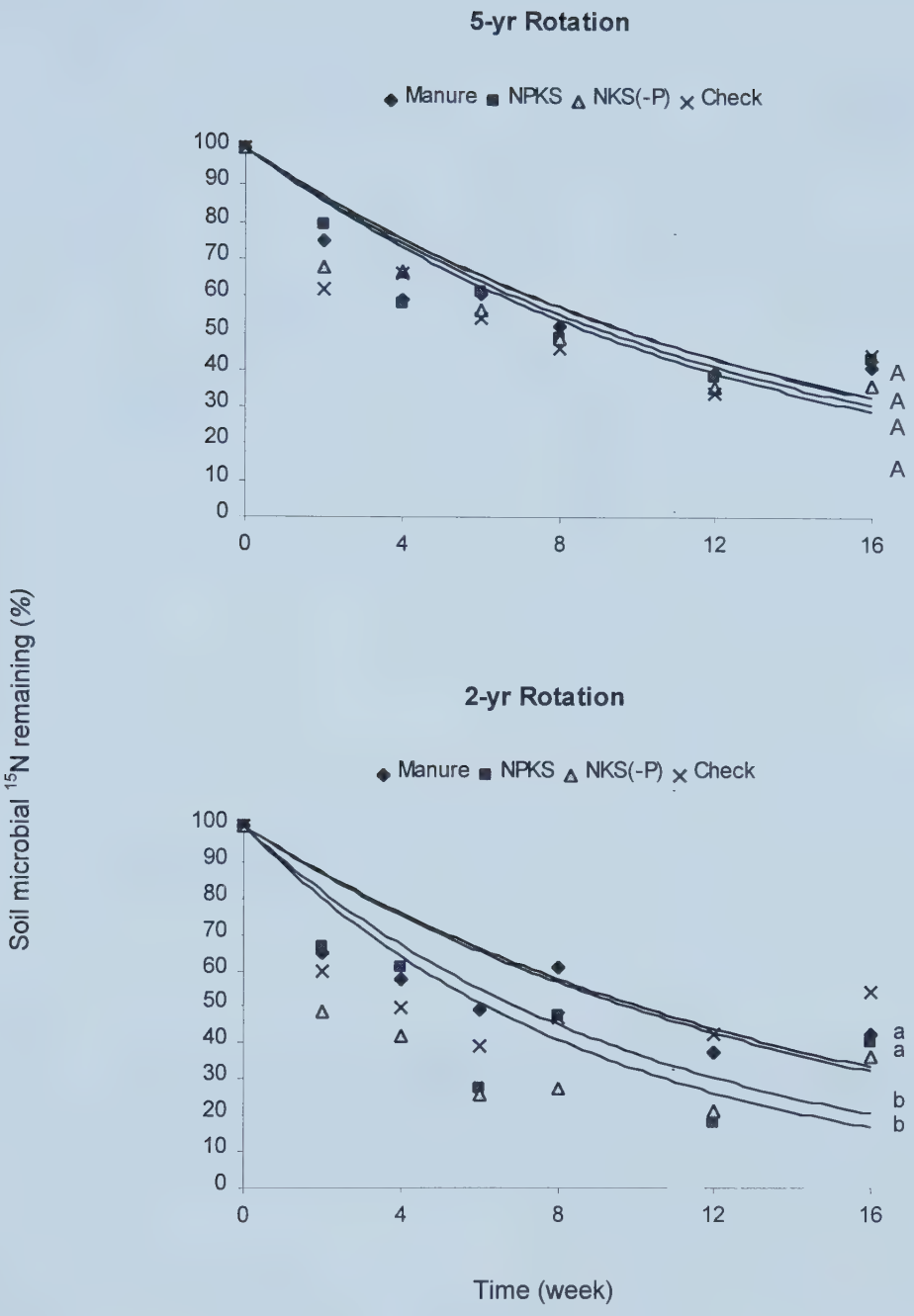

Fig 4.3. Percent of Soil microbial biomass ^{15}N remaining on a relative basis from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD = 10. Slopes of lines carrying the same letter are not significantly different (P>0.05).

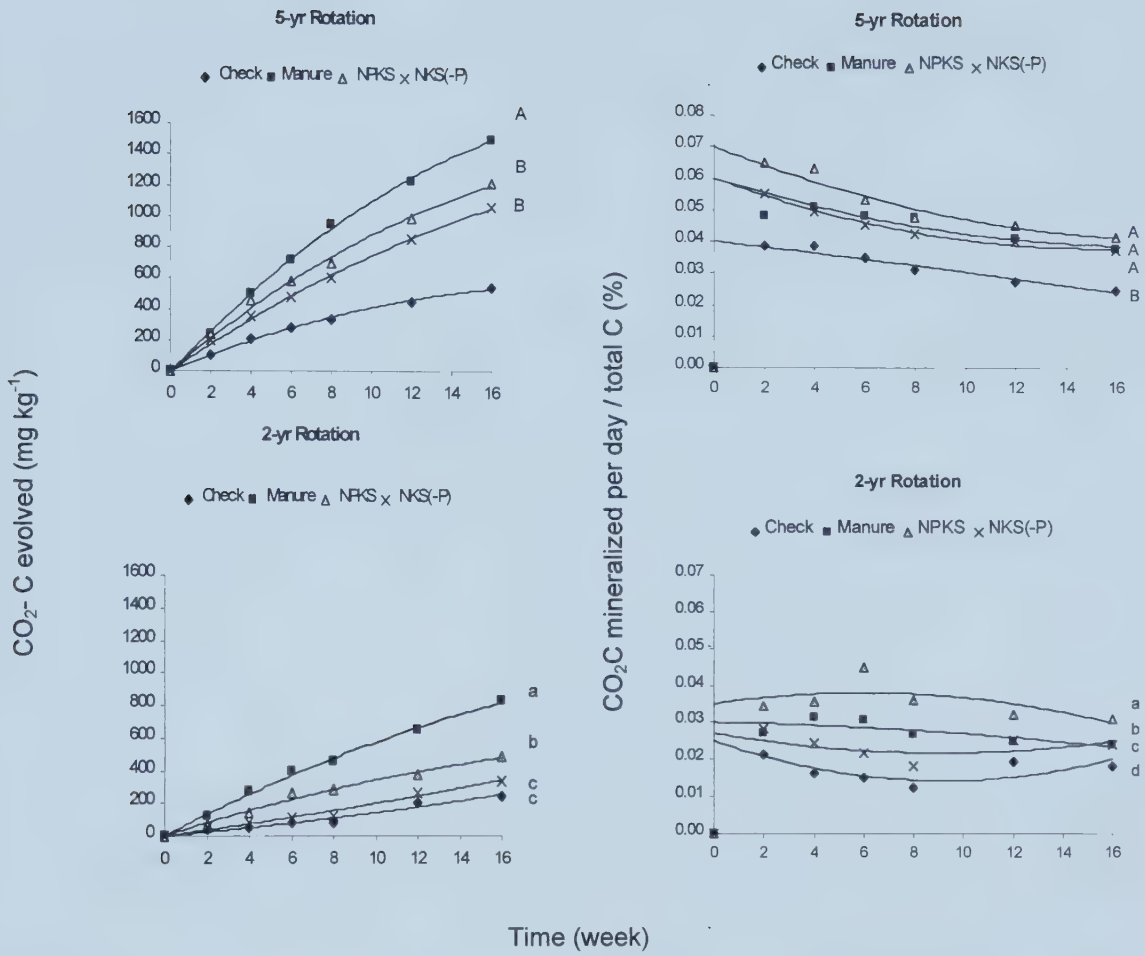

Fig 4.4. (a) Soil cumulative C evolved (mineralized) and (b) percent total C mineralized (cumulative C evolved/ number of incubation days/ total C x 100) from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD: cumulative CO_2-C = 145; C mineralization = 0.003. Slopes of Lines carrying the same letter are not significantly different (P>0.05).

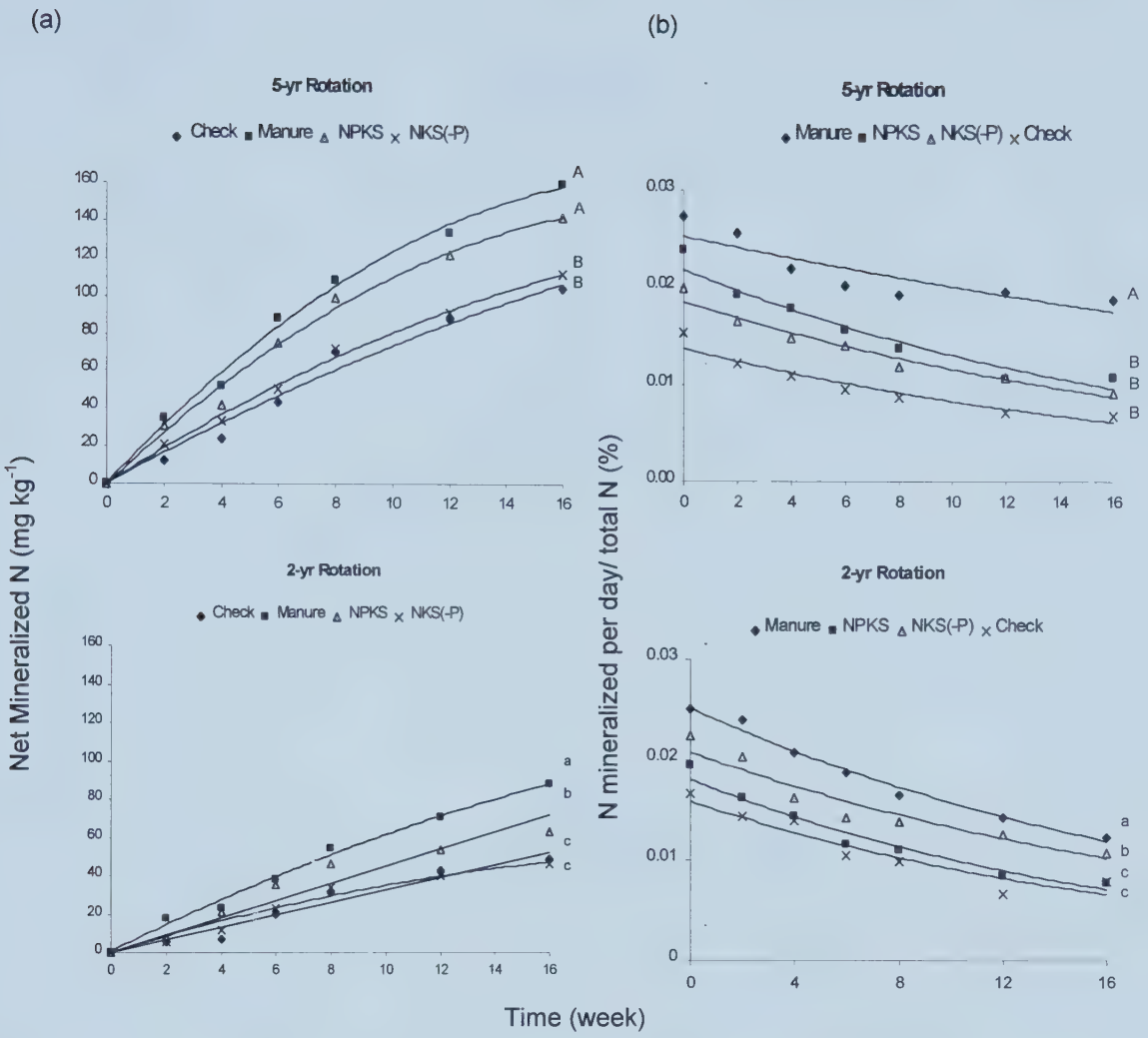

Fig 4.5. (a) Soil Mineral N and (b) percent total N mineralized (cumulative mineral N / number of incubation days/ total N x 100) from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD: cumulative Mineral N = 3.5; N mineralization = 0.011. Slopes of lines carrying the same letter are not significantly different (P>0.05).

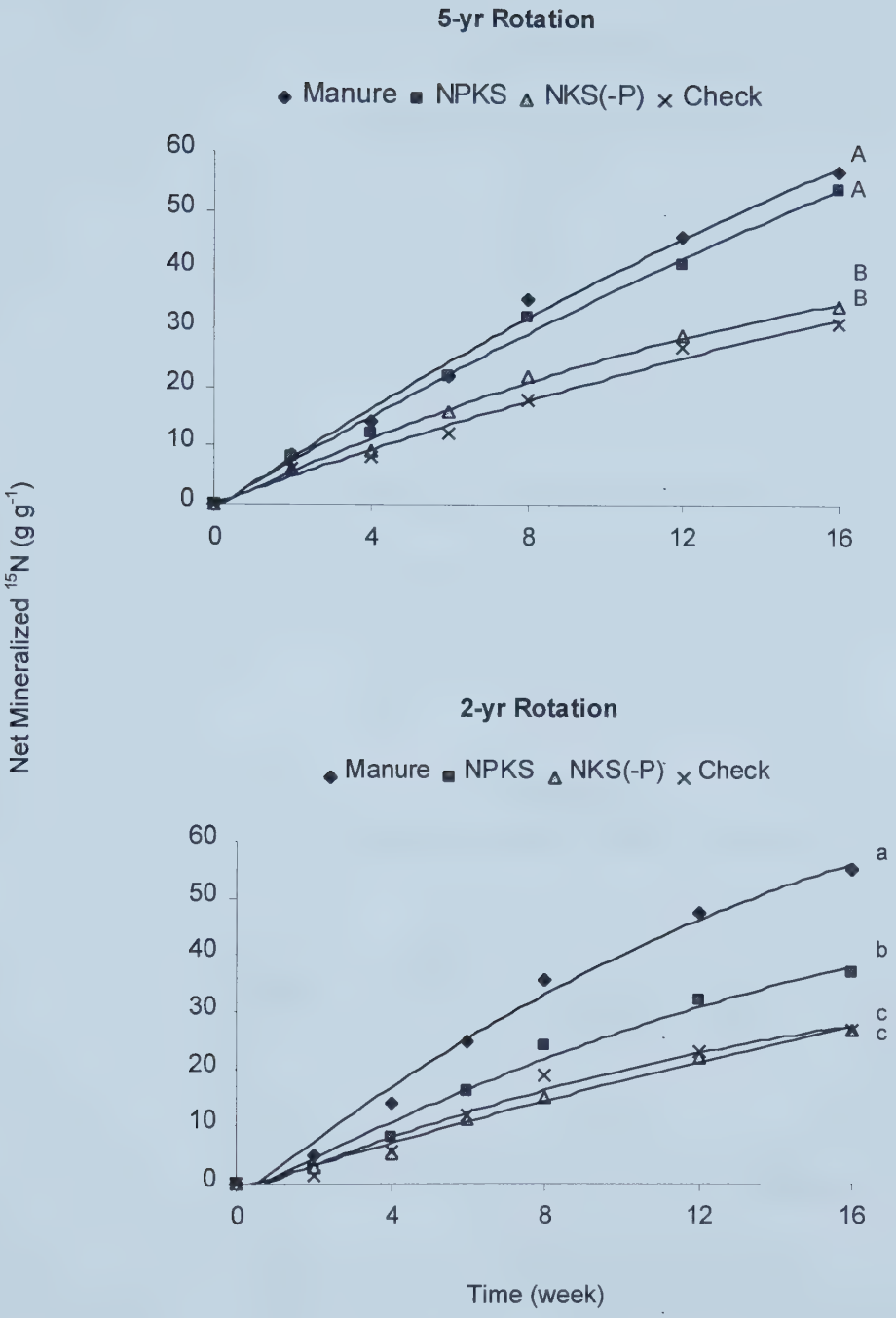

Fig 4.6. The amount ^{15}N mineralized from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD: = 3.8. Slopes of lines carrying the same letter are not significantly different (P>0.05).

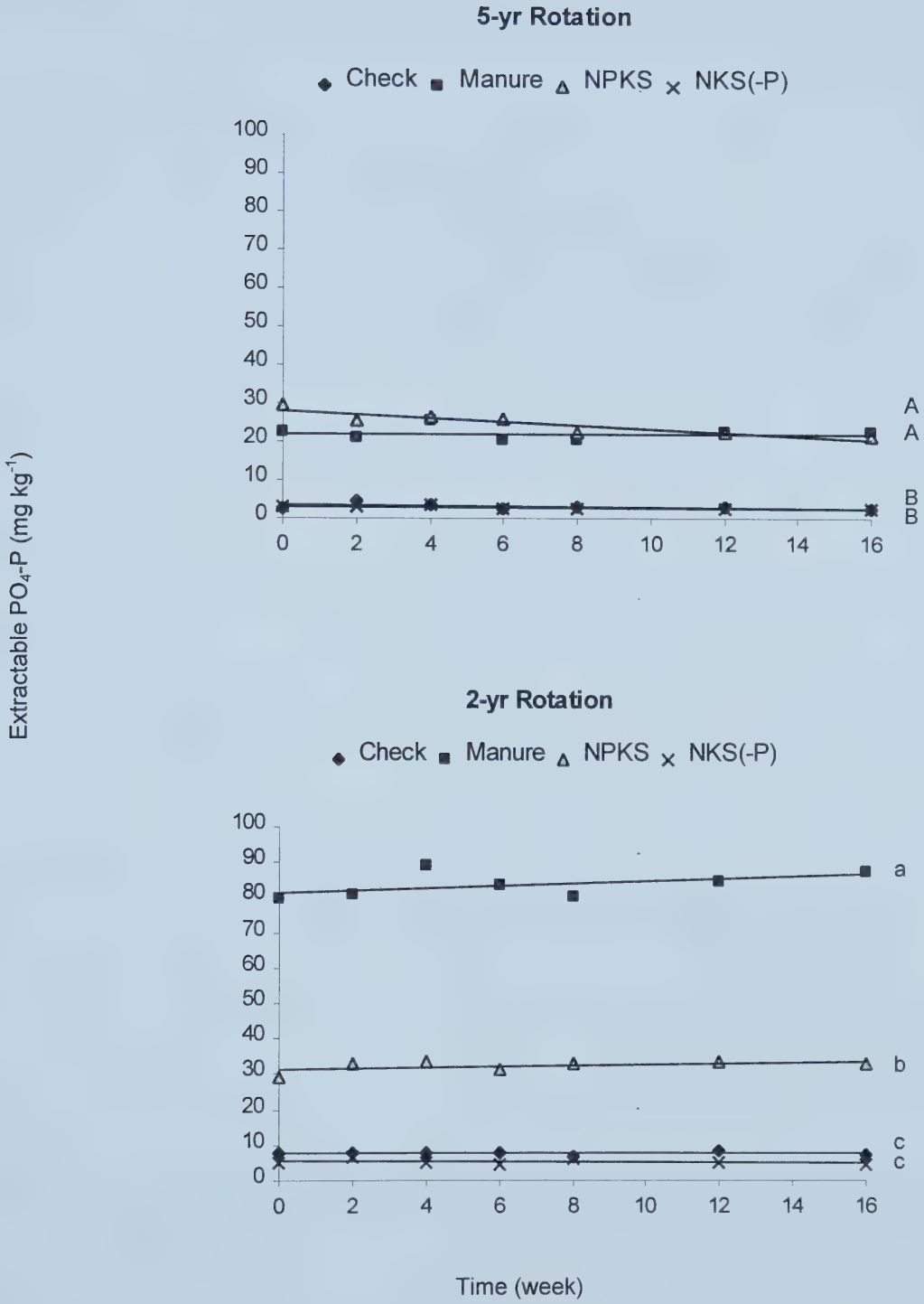

Fig 4.7. Extractable P from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD = 8.5. Slopes of lines carrying the same letter are not significantly different (P>0.05).

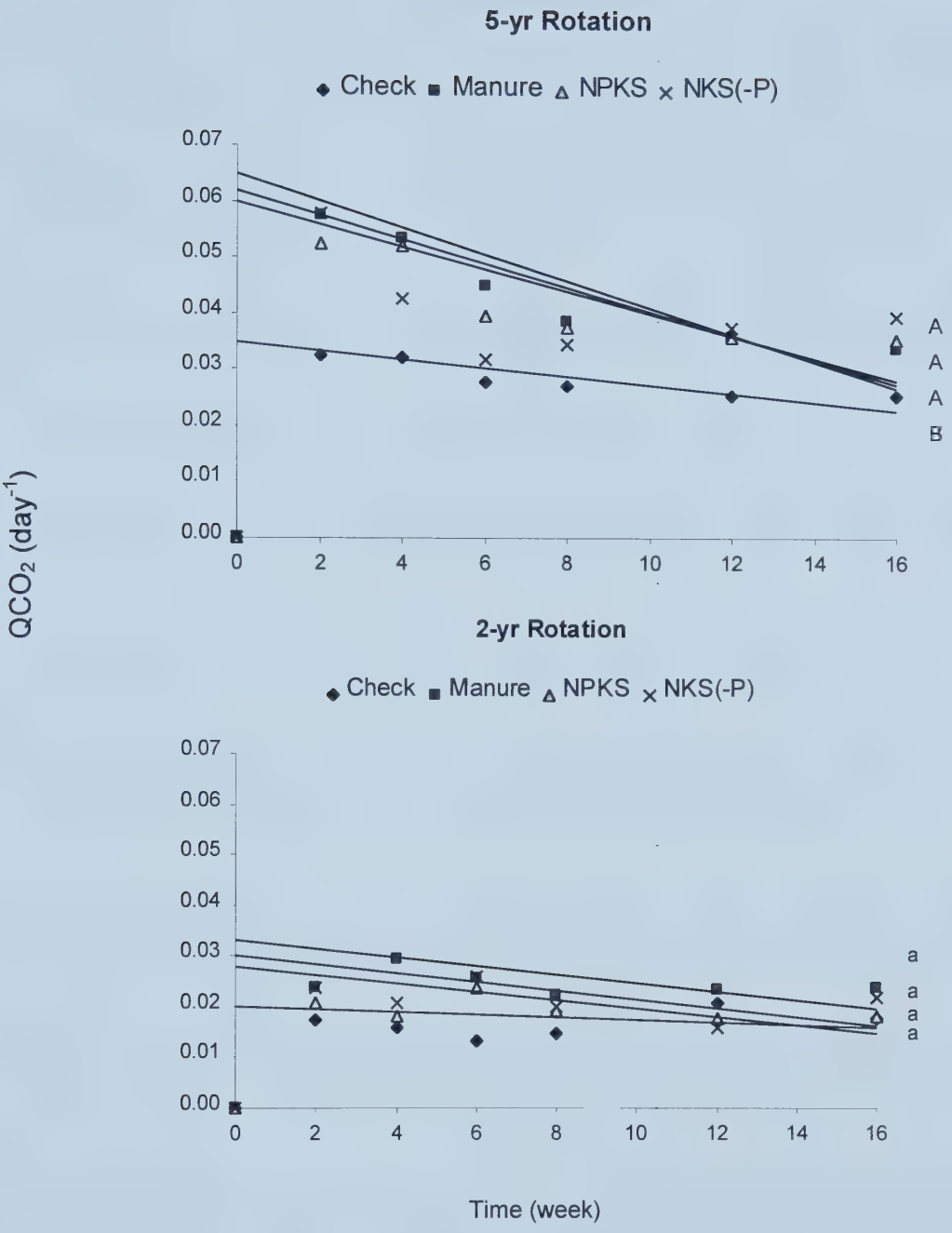

Fig 4.8. Soil respiration activity qCO_2 [CO_2-C (mg kg^{-1} soil day^{-1}) / biomass C (mg kg^{-1} soil)] from the 2-yr and the 5-yr rotations with four treatments at the Breton Plots after 16 weeks incubation; LSD: = 0.003. Slopes of lines carrying the same letter are not significantly different (P>0.05).

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Chapter 5. Synthesis

Over a period of past 70 years, the Breton Classical Plots have yielded a vast array of research information on topics such as soil and plant nutrition, soil management practices, soil organic matter studies, carbon sequestration, greenhouse gas emissions, and nitrate leaching. The Breton Classical Plots have yielded information on soil properties and plant biomass production in the 5-yr wheat-oats-barley-forage-forage and the 2-yr wheat-fallow long-term crop rotations (Robertson 1990; Juma et al. 1997; Izaurralde 2001). The plots are located on fairly level to gently sloping land and more specifically (plots 1-4, series A-F) the plots are relatively level (Fig 1.2). While soil organic matter dynamics were not the initial focus of research on these plots, different nutrient additions (e.g. Manure vs. inorganic fertilizers) and crop rotations led to a greater appreciation of SOM as a source and sink of nutrients (Paustian et al. 1998.)

Phosphorus is an essential nutrient for plant growth and development. The soils at the Breton Plots are deficient in P and require additions of P from either Manure or commercial fertilizer sources to sustain optimum growth. Most microbial processes like mineralization, N fixation and immobilization require P to carry these essential functions. Most of the soil C, N, and S is in organic forms but almost 60% of total soil P consists of inorganic forms in the Ap horizons. Therefore, the dynamics of soil phosphorus are more complex than those of C, N and S because plant available phosphorus originates from several inorganic and organic sources (Hedley et al. 1982).

MAJOR DISCOVERIES

Soil P has not been studied at the Classical Plots in the context of its role in carbon sequestration in the past but has been examined in this study. This is the reason the NKS(-P) treatment was examined in addition to the Manure, NPKS, and Check treatments at the Breton Classical Plots. In Chapter 2, long-term indicators like total C, N, and P and short-term indicators like MOM C, N, and P, mineralizable C and N (without the MOM fraction), extractable P, and microbial C were measured to test the differences between the 5-yr and 2-yr rotations. The major discoveries in Chapter 2 confirmed previous studies that the 5-yr rotation has significantly higher magnitudes of

total, MOM, mineralizable, and extractable C, N, and P in comparison to the 2-yr rotation. The grain and straw yields were significantly lower in the 2-yr rotation compared to the 5-yr rotation. In most cases the NKS(-P) treatment had a significantly lower magnitude of grain and straw, total, MOM, mineralizable, and extractable C, N, and P. The average magnitude of pools and flows in the Manure treatment was between 1.2 to 3 times higher than those in the NKS(-P) and Check treatments. The MOM C:P and N:P ratios were significantly wider in the NKS(-P) and Check compared to the Manure and NPKS treatments. This study supported the premise that net primary production, depending on management practices, would contribute a higher amount of SOM in the 5-yr rotation compared to the 2-yr rotation, especially if fertilized with manure or complete inorganic fertilizers .

In Chapter 3, similar analyses were made as in Chapter 2, however the focus was the impact of lime and P on SOM dynamics. Sampling was done on the limed and unlimed plots of the 5-yr rotations at the Breton Plots. The presence or absence of lime was taken into consideration instead of rotation. In Chapter 3, the unlimed soils had a significantly lower soil pH compared to the unlimed soil. The grain yields were significantly lower in the unlimed plots in comparison to the limed plots. The magnitude of short-term indicators like mineralized C and N were lower in the unlimed compared to the limed plots. However, the extractable P and total P had significantly increased in the unlimed plots, especially in the lower depths and total C and N and MOM C, N, and P were not significantly influenced by the addition of lime. The NKS(-P) and Check treatments were also significantly lower in grain yield, total and mineralizable and extractable C, N and P than the Manure and NPKS treatments. The MOM C:P and N:P ratios were significantly wider in the NKS(-P) and Check treatments compared to the treatments with P. These findings contribute to our understanding of the availability of nutrients through management practices (liming or the addition of organic/inorganic fertilizer treatments) and their influence on net primary production.

In Chapter 4, the focus was directed at unraveling the dynamics of soil C, N and P using ^{15}N-labeled soils obtained from wheat plots of both rotations. Microbial biomass C and N , mineralizable C and N, and extractable P were measured several times over a 16-

week laboratory incubation using the whole soil in contrast to the one time measurements made in the 10 week incubation experiments without the MOM fraction (Chapters 2 and 3). The ^{15}N labeled soil samples from the 0-12.5 cm depth were obtained from microplots established in the Manure, NPKS, NKS(-P), and Check treatments from the 5-yr and 2-yr rotations. In chapter 4, mineral and microbial biomass ^{15}N and specific mineralization rates of C and N were significantly lower in the NKS(-P) and Check treatments. The extractable P was significantly higher in the 2-yr Manure treatment (about 7 times higher than 2-yr NPKS and 8 times as high as the NKS(-P) and Check treatments) (Fig. 4.6) and relatively low in the 5-yr rotation. Extractable P measured over 7 points further revealed that there is equilibrium between plant uptake, soil availability and inorganic mineral pool solubility. Thus, amounts of extractable P did not change over the 16-weeks but there was a stoichiometric relationship between C and N mineralization. The P dynamics are more complex because a significant amount of P is present in inorganic forms.

SYNTHESIS

The chemical elements needed for plants and soil are found in the soil in the form of macro- and micro-nutrients, water, and air. Plant macronutrients include carbon, oxygen, hydrogen, nitrogen, phosphorus, sulfur, potassium, calcium and magnesium. Plant micronutrients include chlorine, iron, manganese, boron, zinc, copper, and molybdenum. The average concentrations of plant macro- and micro-nutrients in a large number of plants are presented in Table 5.1 (Rains 1976, Troeh and Thompson 1993).

Table 5.1 Average concentration of macronutrients and micronutrients in large number of plants (Adapted from Rains 1976, Troeh and Thompson 1993)

Macronutrients	Concentration ($g\ kg^{-1}$)	Micronutrients	Concentration ($g\ kg^{-1}$)
Carbon (C)	450	Chlorine (Cl)	0.10
Oxygen (O)	450	Iron (Fe)	0.10
Hydrogen (H)	60	Manganese (Mn)	0.05
Nitrogen (N)	15	Boron (B)	0.02
Potassium (K)	10	Zinc (Zn)	0.02
Calcium (Ca)	5	Copper (Cu)	0.006
Magnesium (Mg)	2	Molydenum (Mo)	0.0001
Phosphorus (P)	2		
Sulfur (S)	1		

Feedlot cattle manure provides the macro- and micro-nutrients needed for optimal plant growth as well as organic carbon. Eghball and Power (1994) reported that feedlot cattle manure contains 1.9% N, 0.7% P, 2.0% K, 1.3% Ca, 0.7% Mg and 0.5% S on a dry mass basis (Eghball and Power 1994). The iron, manganese, copper, boron, zinc, and molybdenum provided in manure is 5000, 40, 2, 14, 8, and 1 g Mg^{-1} manure (dry weight). Manure also supplies organic C, therefore it is more than just a source of macronutrients. The average concentration of feedlot manure used for the Breton Classical Plots 2.2% N and 0.7% P, respectively. Analysis of other macro-and micro-nutrients have not been conducted, Since 1980, the manure applied to the Breton Classical Plots is 90 kg N ha^{-1} per 2 years in the 2-yr rotation and 88 kg N ha^{-1} per 2.5 years. Therefore, the average rates are 45 kg N ha^{-1} yr^{-1} in the 2-yr rotation and 35.2 kg N ha^{-1} yr^{-1} for the 5-yr rotation. Using a value of 0.7% P, the average rates of P application are 14.3 kg P ha^{-1} yr^{-1} in the 2-yr rotation and 11.2 kg P ha^{-1} yr^{-1} for the 5-yr rotation since 1980. The annual rate of P application in the NPKS is 22 kg P ha^{-1}. Therefore the P added from manure was lower than the P added from the NPKS treatment.

The NPKS treatment contributes inorganic macronutrients to the soil but does not provide the extra carbon and micronutrients that the manure provides. The NPKS provided enough macronutrient to the soil for crop growth but less plant biomass was observed compared to the Manure treatment in both rotations. The NKS(-P) yield was significantly lower than both the NPKS and Manure because the P was not present. However, there was enough N and S to produce a higher plant biomass than the Check treatment. Carbon sequestration is dependent on plant nutrition because the plant biomass provides the below-ground inputs of organic C control microbial activity and formation of humus.

FUTURE RESEARCH

There are several research questions that need to be addressed by future studies:

1. To fully understand the impact of nutrient management on SOM dynamics and nutrient balance in the plant and soil, it is necessary to analyze C, macro- and micro-nutrients of the plant samples and manure annually and soil samples every 5 years for

all half-plots. This would require significant resources because the Breton Classical Plots have a total of 132 half-plots (6 series x 11 treatments x 2 halves);

2. The focus of SOM dynamics and sequestration has been on carbon and nitrogen dynamics in the past. Some studies at Breton have addressed the impact of phosphorus but studies must also address the impact of sulfur on SOM dynamics and sequestration; and

3. A data base of all yields, management practices and carbon, nitrogen, phosphorus and sulfur dynamics needs to be expanded to include the historical context for specific influences on yield and management at the Breton long-term plots. This would provide needed information bridge the past data to the present data.

These suggestion clearly show that the Breton Classical Plots have are a tremendous resource. In his review paper on the fate of long-term research plots, Janzen (1995) concluded that the best justification for the establishment and the maintenance of long-term sites and the data provided is that they provide a vast resource for future scientists posing questions that have not yet been anticipated. Such plots should be valued as a "living and growing library" for questions of both the past and the future.

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APPENDIX A1. Sample Calculations

Total C, N, and P (for all 3 chapters)

Example: 5-yr Manure treatment 0-7.5 cm depth (Chapter 2) the %C = 2.48,

the D_b = 1.2 Mg m^{-3}, therefore Total C:

= 2.48 kg C/ 100 kg soil x 1.2 Mg soil m^{-3} x 0.075 m = 0.002236 Mg m^{-2}

To convert total C Mg m^{-2} to kg ha^{-1}

= 0.002236 Mg m^{-2} x (1000 kg /Mg) x ($10^4 m^2$/ha)

=22 360 kg ha^{-1} = 22 400 kg ha^{-1} to three significant digits

MOM C, N and P (Chapters 2 and 3)

Example: Manure treatment 5-yr rotation in the 0-7.5 cm depth (Chapter 2 (Table 2.4))

MOM magnitude:

= 2.711 g MOM kg^{-1} soil x 0.075 m

= 0.2033 g MOM kg^{-1} m soil x 1200 kg m^{-3} x $10^4 m^2$ ha^{-1}

= 2440 kg MOM ha^{-1}

MOM C:

= MOM amount x % C

= 2440 kg ha^{-1} x 35.25 %

= 859.8 kg ha^{-1} = 860 kg ha^{-1}

Mineralizable N, Biomass N, Extractable P (Chapters 2 and 3)

For the 5-yr Manure treatment in the 0-7.5 cm depth (Chapter 2 (Table 2.6)) the N concentration was in mg kg^{-1}, and D_b = 1.2 Mg m^{-3} = 1200 kg m^{-3}.

Therefore, mineralizable N:

= 73 mg kg^{-1} x 1200 kg m^{-3} x 0.075 m = 8800 mg m^{-2}

To convert mineralizable N mg m^{-2} to kg ha^{-1}

= 8800 mg m^{-2} x (1 kg/10^6 mg) x (10^4 m^2/ ha)

= 64 kg ha^{-1} to two significant digits.

Mineralizable C (For all 3 Chapters)

Example: 5-yr Manure treatment (0-7.5 cm depth in Chapter 2 (Table 2.6))

The mg of CO_2-C/ kg (295.2 mg CO_2-C kg^{-1} soil) was divided by a K_c factor of 0.41 and multiplied by the depth of 0.075 m. and by bulk density of 1200 kg m^{-3} x 10^4 m^2 ha^{-1}

= 295.2 mg CO_2-C / kg soil / 0.41 x 0.075m x 1200 kg m^{-3} x 10^4 m^2 ha^{-1}

= 648 kg CO_2-C ha^{-1}

^{15}N Biomass, ^{15}N Mineralization (Chapter 4)

^{15}N microbial biomass was calculated by subtracting the background atom ^{15}N abundance (0.3683%) from atom abundance $^{15}NH_4$ of labeled soil to get atom % ^{15}N excess and multiplying by the size of microbial biomass

Example: 5-yr Manure treatment

get atom % ^{15}N excess = 0.4676 atom % abundance of labeled soil -
0.3683 background atom % ^{15}N abundance at Breton

^{15}N microbial biomass = 0.00099 x 163 mg N kg^{-1} soil (biomass N- of 5-yr Manure)

= 162 ng g^{-1}

^{15}N mineralized was calculated subtracting the background atom % ^{15}N abundance (0.3683) from atom % abundance $^{15}NO_3$ of labeled soil to get atom % ^{15}N excess and multiplying by the size of mineralized N

Example: 5-yr Manure treatment

get atom % ^{15}N excess = 0.4331 atom % abundance of labeled soil -
0.3683% of background ^{15}N at Breton

= 0.0006477 x 88 mg N kg^{-1} soil

= 57 ng g^{-1}